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Selected Approaches to Pathway Analysis

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Prediction of potential radionuclide exposure and the resulting health risk to individuals working on the site of a mining operation as well as to off-site individuals located down-wind or down-stream of the such an operation, is facilitated by applying well-defined models and well-documented computer codes. Such methodologies and codes may have the advantages of being previously verified and applied, of having readily available data bases, of having supporting codes that may be used to prepare data sets or graph predictions, and of generating hard copy summaries containing intermediate calculations and the results of simulations. Several methodologies and codes developed for application to shallow-land disposal of radioactive wastes are of particular interest. One such methodology and code, PRESTO-II (Prediction of Radiation Effects from Shallow Trench Operations) is designed to evaluate possible doses and risks (health effects) from shallow-land disposal operations. This code, its supporting codes and data bases are discussed, together with several applications.

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INTRODUCTION

PRESTO-II (Prediction of Radiation Exposures from Shallow Trench Operations) is intended to serve as a generic (non-site-specific) screening model for assessing radionuclide transport, ensuing exposure, and health impacts to a static local population for a 1000-year period following the end of low-level radioactive waste (LLW) disposal operations (Fields et al., 1986). Human exposure scenarios include normal releases (including leaching and operational spillage), human intrusion, and limited site farming or reclamation. Pathways and processes of transport from the trench to an individual or population include ground-water transport, overland flow, erosion, surface water dilution, suspension, atmospheric transport and deposition, inhalation, external exposure, and ingestion of contaminated beef, milk, crops, and water. PRESTO-II is available with supporting codes, data bases containing site data for three applications, sample calculations and results, and ample documentation.

PRESTO-II was originally developed for simulation of radionuclide release and transport and evaluation of the possible associated human exposure and associated health risk; however, the model has considerable potential for estimating possible consequences associated with mining operations.

The PRESTO-II methodology may be applied to evaluate doses and health risks from a variety of mining activities. This methodology has been implemented in the form of a computer code that has been applied to several sites, and that has been extensively documented. Radionuclide inventories are initially specified as separate contamination sources either present on the ground surface, covered by non-radioactive soils but lying above the water table, suspended in the atmosphere, or dissolved in surface waters. Hydrologic transport mechanisms considered in the PRESTO-II methodology include chemical exchange, ponding and overflow, surface water transport, groundwater transport, and pumping contaminated groundwater from wells. Varied scenarios of water usage are treated. Site activities that may be considered include land clearing, farming, and residing on the site. Exposure and dose calculations are derived from the U.S. Nuclear Regulatory Commission Reg. Guide 1.109 approach (USNRC, 1977), while risk calculations use a life-table approach developed for the U.S. Environmental Protection Agency (EPA). Internal dose conversion factors are taken from ICRP 26 and 30 (ICRP 1977 and ICRP, 1979), while risk conversion factors are values suggested by EPA.

THE PRESTO-II METHODOLOGY AND CODE

In PRESTO-II, human exposure scenarios include normal releases (including leaching and operational spillage), human intrusion, and limited site farming or reclamation. Pathways and processes of transit from the trench to an individual or population include ground-water transport, overland flow, erosion, surface water dilution, suspension, atmospheric transport, deposition, inhalation, external exposure, and ingestion of contaminated beef, milk, crops, and water. The health risk estimation approach assumes that each member of the population is a member of a cohort that is exposed to constant, annual-averaged radionuclide concentration levels. Risk calculations are made in PRESTO-II using the DARTAB model, which has been separately documented (Begovich et al., 1981). PRESTO-II computes risk values using dose-to-risk conversion factors contained in the 1981 version of the RADRISK data set (Dunning, Leggett, and Yalcintas, 1980; Sullivan et al., 1981).

The PRESTO-II methodology and code have been well-documented. A code listing and example input for each of three example sites have been published (Fields et al., 1986). Also included in this report is a sample run. PRESTO-II, DARTAB, and PRESTO-PREP are available at no charge from the Radiation Shielding Information Center (RSIC) at Oak Ridge National Laboratory.

The PRESTO-II code tracks radionuclide transport through surface and subsurface pathways and human exposures through external exposure, inhalation, and ingestion, with a resolution of 1 year (some processes are simulated with higher temporal resolution, and the results applied within portions of the code having a 1 year resolution). The methodology is mechanistic and physical transport processes are modeled separately and in detail. Valid results require adequate knowledge of site variables. Source terms are initial radionuclide distributions in the atmosphere, streams, land surfaces, and in subsurface trenches. Human exposure scenarios include migration of radioactivity from the trench in hydrologic and atmospheric environmental pathways to food and drinking water. At-risk individuals and populations include those ingesting contaminated on-site or off-site food and water, breathing contaminated off-site or on-site air, undergoing external exposure to ground surface contamination, or living in an on-site basement.

Water, principally from precipitation, is often a primary transport medium for radioactivity from low-level radioactive waste stored in shallow trenches. Hydrologic pathways considered in the PRESTO-II methodology are shown in Figure 1. Precipitation or irrigation water falling on the waste disposal site may either infiltrate the soil or trench cap, run off the surface, or evaporate, and radionuclides may be transported from a LLW disposal trench by groundwater or by precipitation runoff. Runoff also causes erosion of the soil surface and erode the trench cap. Contaminated water that percolates downward through the trench to the soil zone beneath the trench may ultimately enter an aquifer. Radionuclides that finally reach the aquifer will generally be transported more slowly than the characteristic flow velocity of water in the aquifer because the radionuclides interact with the solid materials in the aquifer. Some of the radionuclides which enter the aquifer may eventually reach irrigation or drinking wells or surface streams. Contaminated water from the trench may overflow onto the surface soil (the "bathtub effect"). Once overflow has occurred, radionuclides may be transported by runoff water to nearby streams and become available for human consumption via irrigation or drinking. Humans may also be exposed to radionuclides transported from LLW sites by atmospheric processes.

Atmospheric transport processes are included in the PRESTO-II methodology. As shown in Figure 2, radionuclides left on the soil surface by trench overflow, by spillage during disposal operations, or by complete removal of the trench cap may be suspended in the atmosphere and transported downwind where they may be inhaled or deposited on vegetation and soil. In the case of deposition, the radioactivity may produce external exposure to humans or may enter into the food chain and result in radioactivity in crops, meat, and milk. Downwind radionuclide concentrations are calculated from atmospheric inputs using either a resuspension factor or a resuspension rate approach (Fields, 1983), with inhalation and immersion doses based on a Gaussian plume transport calculation. For atmospheric transport calculations, the total population is assumed to reside within the same 22.5-degree sector. User-specified parameters give the fraction of the year that the wind blows into that sector. A user option allows the results of the atmospheric dispersion calculation in the code to be replaced by an externally calculated dispersion coefficient which considers several population centers.

Processes considered in calculating individual or population exposure include groundwater transport, precipitation runoff, trench water overflow and seepage, chemical exchange, trench cap erosion, stream dilution, and resuspension and atmospheric dispersion of contaminated soil followed by inhalation or oral and external exposure subsequent to deposition on crops and land.

The termination of LLW disposal operations (as associated with final trench closure) is the starting time for the total assessment period considered by the code. The user specifies the total length of the assessment period, from 1 to 1000 years. The health effects for a user-specified length of time within this assessment period are calculated. The averaging time for health effects can be as short as any single year of the assessment period or as long as the entire assessment period. The maximum concentration of each radionuclide and the year of this maximum for each of the four major exposure pathways for each nuclide is calculated. The initiation time and period for mechanical suspension of the surface soil by farming is specified by the user. The user can also specify the time at which the trench cap begins to fail and the temporal profile of this failure, which results in exposure of the trench contents. The primary code time step is fixed at one year, while the printout interval is user-specified.

The resident intruder scenario assumes that an intruder digs into the disposal trench while building a residence. The individual will receive external exposure to the buried radionuclides due to time spent in the basement of the residence, which is assumed to have walls made of trench material. The user-specified length of residency, time in the assessment period when the residence is first occupied, and the composition of the initial trench inventory will all contribute to the dose from external exposure.

Farming the site after loss of institutional control is treated as a separate intrusion scenario. By farming the site a farmer will be affected by most of the hydrologic and atmospheric transport processes described above. In contrast to an off-site population, however, a larger portion of the farmer's food may consist of crops grown in the contaminated zone near the trench. The water used by the farmer for irrigation, drinking, and livestock may be taken from directly beneath the trench or from a nearby stream and thus contain a much higher concentration of radioactivity than water used by the off-site population. The farming process may also mechanically suspend contaminated soil in the atmosphere. Such mechanical suspension may impact both the farmer and a downwind population.

Annual-average concentrations of each radionuclide in environmental media (such as well water or the atmosphere) over the assessment period are used to calculate radionuclide concentrations in foodstuffs. Foodstuff information and human ingestion and breathing rates are utilized to calculate the annual average radionuclide intake per individual in the population by ingestion and inhalation. These intake data are used by the exposure and risk submodels to estimate dose rate and health risk. Each member of the population is assumed to eat the same quantities of food (vegetables, beef, and milk). These foods are assumed produced on the same fields and spray irrigated with contaminated water. Contaminated water is assumed to be drunk by beef and dairy cattle. The code user may independently specify the fractions of water taken from wells or streams and used for human consumption, for irrigation, or for livestock consumption.

The PRESTO-II code construction is modular to allow alternate submodels or subroutines to be substituted if necessary. Many of the submodels included in PRESTO-II were developed for other types of assessments and have been adapted for use in estimating health effects from shallow land disposal of LLW.

The code contains algorithms to track both radionuclide amounts and radionuclide concentrations in well water. This approach permits the code to correctly conserve radionuclide mass. Radionuclides are first withdrawn from the well for human ingestion in an amount appropriate to the number of exposed persons specified, and remaining radionuclides may be withdrawn to be used for irrigating crops and watering livestock. A second reason to account for both amount and concentration of radionuclides at the well is to insure that the amount withdrawn at the well (based on the calculated concentration at the well) does not exceed the amount available. As a result of this calculation, the dose and risk calculated for a single individual may exceed the dose and risk calculated for individual members of a large population taking water from a well.

PRESTO-II, like any complex computer code, may be misapplied. Misapplication may consist of trying to apply the code to examine a site where one or more modeling assumptions are invalid, or of choosing values of input parameters that do not accurately reflect variables such as radionuclide inventory, site meteorology, surface and subsurface hydrology and geology, and future population demographics. One serious misapplication of the PRESTO-II methodology would be to use inappropriate k_d values to determine hydrologic transport. Element-specific values of k_d vary widely as sites, chemical forms, and other waste components are changed.

Some release and transport scenarios, such as those necessary to consider major meteorological changes, in-situ combustion of trench wastes, and intrusion and radionuclide transport by burrowing animals or plant roots, are not considered in the PRESTO-II model and code.

AUXILIARY PROGRAMS

To assist the PRESTO-II user in compiling radionuclide data, a radionuclide Daughter Inventory Generator (DIG) computer code has been written (Fields and Sharp, 1985). This code facilitates the preparation of the LLW disposal site inventory radionuclide data set for the PRESTO-II code. The DIG code accepts a table of radionuclide names and amounts initially present in a waste stream and produces a tabulation of radionuclide names and amounts present after a user-specified elapsed time. This resultant radionuclide inventory characterizes wastes that have undergone radioactive decay and daughter ingrowth before leaching and transport, thus identifying daughter radionuclides that should be considered for inclusion in the pollutant source term. The output of the DIG code also includes radionuclide decay constants, which are required in the PRESTO-II code input data set.

A second code has also been written to assist the user in preparing PRESTO-II data sets. This second code, which is included in the RSIC code package for distribution with PRESTO-II, is PRESTO-PREP (Bell, Emerson, and Fields, 1984). The PRESTO-PREP code accesses radionuclide data bases to prepare a radionuclide data set in the proper format for reading by PRESTO-II.

The DARTAB model has been separately documented (Begovich et al., 1981), as has the RADRISK data set (Sullivan et al., 1981). The DARTAB code is also available from RSIC.

DATA LIBRARIES

There are basically three types of data that are needed to execute PRESTO-II. They are (1) site-specific and radionuclide data used in transport section of the code for calculating radionuclide concentrations, (2) data used specifically by DARTAB and submitted for creating tabular output, and (3) dosimetric and health effects data (created by RADRISK) used also by the DARTAB code. Data types (1) and (2) must be prepared by the code user while type (3) is furnished on magnetic tape in card image form for the RSIC version of PRESTO-II. Sample site data sets and a copy of the RADRISK data set are provided with the PRESTO-II code and discussed in the documentation.

CODE APPLICABILITY

PRESTO-II is a computer code developed to estimate possible health effects from surface and near-surface contamination. As previously mentioned, the code is also applicable to sites where radionuclides are mined. As an initial condition, up to 40 radionuclides may be specified according to the mass of each radionuclide present on the soil surface, in the air, in a local stream, or in a trench. As presently structured, the code can be used to make estimates for a period of up to 1000 years. The code is intended to be as generic as possible. Most of the transport methodology is derived from previously published work; e.g., (USNRC, 1977). Different transport mechanisms may be considered, but there has been no intent to tailor the code to a particular site. Nevertheless, the assumption in the PRESTO methodology of saturated hydrologic transport results in the prediction of more rapid radionuclide transport than would actually occur at some arid sites. In most cases, the model results are conservative for such sites.

The PRESTO-II model is most appropriately used as a screening model, and site specific codes should be considered in cases where PRESTO-II numerical results fall close to reference values used for decision making. The model may be used to estimate doses to populations as an aid to the ALARA process. It may also be used to estimate doses to maximally exposed individual members of the public by specification in the input data that the location of the individual and of the well, used for obtaining water for drinking, crop irrigation, and livestock watering, is at the site boundary.

Use of PRESTO-II to calculate population doses for considerations of ALARA, or to calculate maximally exposed onsite or offsite individual doses for consideration of compliance with maximum exposure regulations, is determined by the user's choice of population size, well location, and other input option values and parameters.

APPLICATIONS TO SITES IN THE USA AND TURKEY

The PRESTO-II code has been applied to simulate transport from three low-level waste disposal sites in the United States (Fields et al., 1986). Input data were compiled for each of three example locations: Barnwell, South Carolina; Beatty, Nevada; and West Valley, New York. Due to the lack of availability of some data, these data must be regarded as example values designed to verify operation of the code, rather than as unanimously agreed upon numerical specifications of these sites. Results from each of the three sites suggest that there may be low health risk to nearby populations from shallow land disposal of LLW. A summary of results for one scenario at the Barnwell site is presented in Table I.

In a second set of applications of PRESTO-II, this methodology and code has been used to support consideration by the U.S. Nuclear Regulatory Commission of a de minimis disposal standard for certain waste streams (Fields and Emerson, 1984; Fields, 1984).

Furthermore, it has been shown that PRESTO-II has applicability to decontamination and decommissioning sites (Fields, 1986).

The Turkish Government is in the process of planning two nuclear reactors in Turkey. Studies have begun to develop procedures for improved control of low level wastes in Turkey prior to reactor construction. PRESTO-II has been used to assess the risk associated with the shallow land disposal of low level radioactive waste (LLW) in various sites in Turkey.

A preliminary simulation using the PRESTO-II computer code (Fields, Uslu, and Yalcintas, 1987) has been run for the site in Koteyli-Balikesir, Turkey (DSI, 1984). This simulation was performed using the same radionuclide data set believed representative of the LLW disposal facility in Barnwell, South Carolina (Fields et al., 1986). Site environmental variables were selected to typify credible worst case exposure scenarios. Radionuclide inventories are primarily based on estimated waste composition rather than measured values.

Results of these simulations have been compared to those obtained for the Barnwell, South Carolina, site, as summarized in Table 1. These calculations were based on a number of conservative assumptions about the initial radionuclide inventory (Fields et al., 1986). Dose estimates for both sites are below regulatory limits, for the release and exposure scenarios considered. The doses for the sites are comparable with slightly higher estimates obtained for the Turkish site.

Table 1. Results of example problem based on Barnwell, SC data.

Site	Barnwell, S. C.
Population	7033
Deaths/year	5.5E-4
Annual risk per person	7.2E-8
Contributions to net annual death rate by pathway or mode	
INTERNAL	5.5E-4
INGESTION	5.5E-4
INHALATION	1.8E-14
EXTERNAL	9.1E-13
AIR IMMERSION	2.3E-17
GROUND SURFACE	9.1E-13
Contributions to net annual death rate by radionuclide (20 selected radionuclides):	
H-3	2.6E-14
C-14	2.5E-5
Mn-54	2.1E-16
Fe-55	3.6E-16
Co-60	3.6E-13
Zn-65	3.8E-16
Sr-90	7.9E-16
Tc-99	5.3E-4
Cs-134	3.2E-14
Cs-137	2.3E-13
Ba-137	5.8E-13
Ce-144	2.2E-20
Pb-210	4.1E-17
Ra-226	4.8E-19
Th-232	7.4E-18
U-234	1.1E-17
U-235	1.6E-17
U-238	1.1E-14
Pu-238	1.6E-18
Pu-239	2.9E-18

Table 2 summarizes the simulation results of the dose and health effects for Barnwell site and Koteyli site associated with the radionuclide data set believed representative of the LLW disposal facility in Barnwell, South Carolina. These simulation results must be generally regarded as estimates based on the assumptions about waste stream composition, disposal methodology, and site geography. The simulation results presented in Table 2 indicate that relative human radiological impacts for these sites according to the relative gross radioactivity of the streams. Lower consequences are predicted for the Barnwell, South Carolina site, relative to the Koteyli, Turkey site but this conclusion results largely from the assumption that the Koteyli, Turkey site may eventually be used for farm land. If the Koteyli, Turkey site were not irrigated, predicted consequences for this site would be considerably lessened.

Table 2. Summary of the population doses and health effects for the Barnwell Site and Koteyli sites.

	Koteyli	Barnwell
Lifetime fatal cancer risk	$1.68\ 10^{-4}$	$0.56\ 10^{-5}$
Health Effects (Deaths/y)	$2.04\ 10^{-2}$	$5.53\ 10^{-4}$

The sum of all radiological impacts from exposure of the local population of 7033 persons to contaminants in all low-level waste disposal areas near Barnwell is $5.53\ 10^{-4}$ deaths/y. By comparison, the current annual death rate from cancer for a representative population of 7033 is 13 persons (Lane, 1982). The waste disposal-associated death rate is less than the background cancer death rate by a factor of $4.2\ 10^{-5}$.

CONCLUSIONS

PRESTO-II, while designed for simulating radionuclide transport and human exposure associated with LLW sites, has characteristics that make it useful in evaluating possible consequences from radionuclide releases from mining operations. The code is documented and has been applied to various sites. In addition to the code itself, several supporting codes and methodologies, including PRESTO-PREP, DIG, and DARTAB, have also been documented. PRESTO-II is available in computer-readable form together with supporting codes, data bases containing site data for three applications, sample calculations and results, and ample documentation.

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