COMPREHENSIVE TRANSPORTATION RISK ASSESSMENT SYSTEM BASED ON UNIT-CONSEQUENCE FACTORS*

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ABSTRACT

The U.S. Department of Energy (DOE) Environmental Restoration and Waste Management Programmatic Environmental Impact Statement requires a comprehensive transportation risk analysis of radioactive waste shipments for large shipping campaigns. Thousands of unique shipments involving truck and rail transport must be analyzed; a comprehensive risk analysis is impossible with currently available methods. Argonne National Laboratory developed a modular transportation model that can handle the demands imposed by such an analysis. The modular design of the model facilitates the simple addition/updating of transportation routes and waste inventories, as required, and reduces the overhead associated with file maintenance and quality assurance. The model incorporates unit-consequence factors generated with the RADTRAN 4 transportation risk analysis code that are combined with an easy-to-use, menu-driven interface on IBM-compatible computers running under DOS. User selection of multiple origin/destination site pairs for the shipment of multiple radioactive waste inventories is permitted from pop-up lists. Over 800 predefined routes are available among more than 30 DOE sites and waste inventories that include high-level waste, spent nuclear fuel, transuranic waste, low-level waste, low-level mixed waste, and greater-than-Class C waste.

INTRODUCTION

A comprehensive transportation risk analysis of radioactive waste shipments for large shipping campaigns has been developed in support of the U.S. Department of Energy (DOE) Environmental Restoration and Waste Management (EM) Programmatic Environmental Impact Statement (PEIS). In part, the EM PEIS is being undertaken to assess the impacts of various treatment and disposal options for existing and future radioactive waste at DOE facilities. The implementation plan (1) for the EM PEIS requires the assessment of thousands of unique shipments. A specific radionuclide inventory shipped over a specific route constitutes a unique shipment for which a separate set of estimates must be calculated. For each unique shipment, the analyst must be concerned with a number of input parameters related to the incident-free transport of the waste in addition to parameters related to the potential accidental release of some or all of the shipment contents. A modular transportation model was developed by using unit-consequence factors to handle the workload.

The majority of previous transportation risk assessments have been conducted with national-level data and the RADTRAN 4 computer code (2) or one of its predecessors. Current data are sufficient to warrant a level of detail down to the state level; in some cases, down to three population zones (rural, suburban, and urban) on a state-by-state basis. A typical route can span anywhere from 1 up to about 12 or 13 states. A computer run of the RADTRAN 4 code can assess the impacts for the rural, suburban, and urban zones in the same run but only for one set of parameters (state-specific), such as accident rates and portion of travel, in each zone. Consequently, a computer run of the RADTRAN 4 code must be set up, executed, compiled, and checked for each state traversed in each route, for each source term, and for each transport mode (e.g., truck or rail). Tens of thousands of these runs involving truck and rail transport are required for the EM PEIS. This task is impractical without the use of unit-consequence factors.

Fortunately, the structure of the RADTRAN 4 code facilitates the use of unit-consequence factors. McSweeney and Basinger (3) developed unit-risk factors for the assessment of spent nuclear fuel (SNF) shipments of boiling-water reactor and pressurized-water reactor fuel. For both incident-free and accident conditions, the study used only national-level data; the results are specific to the two types of SNF and the accident release characteristics of their spent fuel shipping casks. We have taken the concept further with the use of unit-consequence factors rather than unit-risk factors.

As shall be demonstrated, unit-consequence factors can be used to provide a comprehensive transportation analysis of radioactive waste shipments for even the largest shipping campaigns without loss of detail. Only truck and rail transport modes are considered. This approach provides many benefits. First and foremost, the analysis becomes tractable for the highest level of detail possible. Quality control complications are greatly reduced as are computational times for health risks and the overhead associated with file space and management. In conjunction with a modular design, this approach is highly flexible and permits the easy addition of transportation routes, waste package characteristics, and source terms as needed.

APPROACH

Input data for radioactive transportation risk assessments are easily categorized and relatively independent of one another. These conditions suggest a modular approach that greatly simplifies the task of preparing and checking input data/files and also fits well with the use of unit-consequence factors. For example, radioactive waste (source term Z) is placed in a package X that is shipped from Site 1 to Site 2 over a given route through states A, B, and C. Source term Z is itself composed of radionuclides 1-5. The available input

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parameters necessary and specific to the RADTRAN 4 analysis of a unique shipment for incident-free transport include the following:

1. Package characteristics
   - Largest dimension of package X
   - Transport index for package X (external dose rate at 1 meter from the package surface)
2. Route characteristics
   - Distance traveled on the route in each population zone of states A, B, and C
   - Population density in each population zone of states A, B, and C traversed by the route

For accident risk estimates, the available parameters specific to the shipment include the following:

1. Package characteristics
   - Radionuclide release and dispersal fractions for different accident severity categories for package X
2. Route characteristics
   - Distance traveled on the route in each population zone of states A, B, and C
   - Population density in each population zone of states A, B, and C traversed by the route
   - Accident frequencies in each population zone of states A, B, and C traversed by the route
   - Food transfer factors for radionuclides 1-5 for each of the states A, B, and C for calculation of the ingestion pathway
3. Source term
   - Radionuclide inventory by isotopic curie (Ci) content; that is, Ci of radionuclides 1-5 (source term Z) present in package X

Obviously, there is a clear distinction between what is being shipped, package X, and the route from Site 1 to Site 2 that the package takes to arrive at its destination by truck or rail. The characteristics of package X and its contents, source term Z, are independent of the route. Package X and its contents might also have to be shipped from Site 2 to Site 3, but the route will be different. Therefore, a routing database can be developed without having to consider what is being shipped. Potential routes must be known beforehand; however, it is easy to add routes to the database when necessary by using this modular approach.

The source term Z and the characteristics of package X cannot be so clearly delineated. The shipping package to be used will depend on the radionuclides being shipped, but a given package type may be used for a range of radionuclide inventories, thus allowing for some flexibility in the design of a transportation model. In other words, package X may be used for the transportation of different source terms other than for radionuclides 1-5.

Other required data, such as the accident frequencies along the route in each population zone in states A, B, and C and the food transfer factors for radionuclides 1-5 in states A, B, and C, can be considered independent of the specific route from Site 1 to Site 2 and source term Z. These data can be compiled independently and placed in data files for retrieval when necessary. The overall available data on accident frequencies are not detailed enough for a breakdown more specific than the generic population zone. Routes 30 and 45 in state A will be assumed to have the same accident rates if they are both passing through a rural population zone. Likewise, as long as you are in state A, the food transfer factor for radionuclide 1 will be the same. The data on food transfer factors can be compiled once; all information on radionuclides considered for all 48 contiguous states can be placed in a separate data file. With this modular approach, it becomes straightforward to maintain and update data when the need arises, for example, the addition of another radionuclide to the database.

IMPLEMENTATION

Figure 1 is a diagram of our transportation assessment model. For a given unique shipment, such as package X with source term Z shipped from Site 1 to Site 2, the incident-free risks are estimated simply by scaling the unit-consequence factors by the population zone densities (rural, suburban, and urban) and the distance traveled in each population zone in states A, B, and C. For the accident risks, the unit-consequence factors only for the isotopes present in the shipment, that is, radionuclides 1-5 in source term Z, are scaled by the Ci content of each radionuclide in the shipment; the distance traveled in each population zone in states A, B, and C and the accident probabilities in each of these zones; the state food transfer factors for radionuclides 1-5 in states A, B, and C; and the frequencies of accidents in each severity category for the transportation mode, truck or rail, and their associated release, dispersal, and aerosolized fractions for package X.

Incident-Free Unit-Consequence Factors

Incident-free risks are calculated for four receptors: the transportation crew, persons traveling along the route with the shipment (on-link population), persons along the sides of the route (off-link population), and persons at rest stops along the way. Unit-consequence factors (estimated dose in person-rem) for each receptor are calculated on a per-kilometer basis for each population zone and each transportation mode (truck and rail) assuming a population density of 1 person/km^2 and a fixed transportation index and package dimension. Because of such input considerations as the fraction of city streets traveled and the fraction of travel during rush hour for truck transport and differences in one-way traffic densities between truck and rail modes, separate RADTRAN 4 runs are required for each population zone and transport mode. Six total runs are necessary to generate the unit-consequence factors for incident-free analysis. The final consequences are determined by scaling the unit-consequence factors by the population zone densities, by the distances traveled in each population zone over all states, and finally by correcting for the actual transport index and package dimension according to RADTRAN 4 methodology.

Accident Unit-Consequence Factors by Isotope

The accident risk to the off-link population is estimated by first calculating state unit-risk factors. Unit-risks per kilometer are calculated for the three population zones in each state traversed by the transportation mode under consideration. The state unit-risk factors are then scaled by the appropriate population densities and the distance traveled in each population zone and summed together to get the total accident risk to the general public.

Equation 1, derived from RADTRAN 4 methodology, for calculating the state unit-risk factors is the key to our

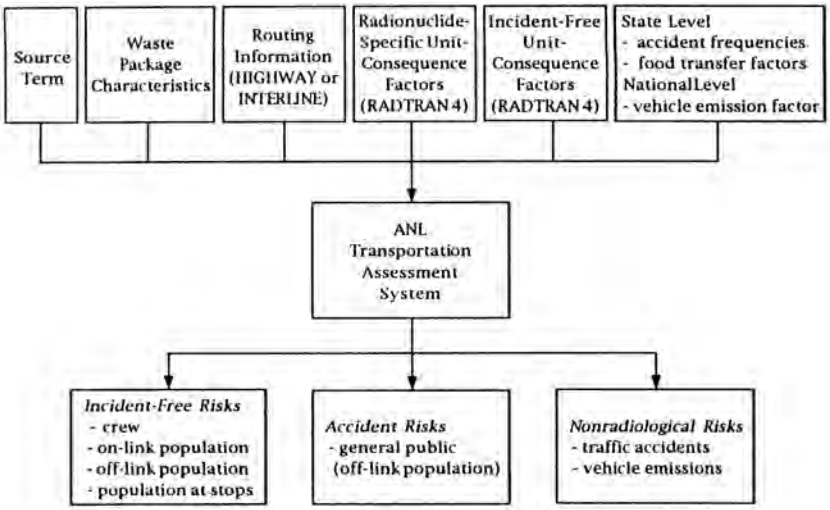

Fig. 1. ANL transportation assessment model.

approach. It provides the modularity necessary to make the unit-consequence factors (D_{jkm}) independent of accident probabilities (P_{ij}); release (RF_{ko}), aerosolized (A_{ko}), and respirable (R_{ko}) fractions; and food transfer factors (F_{ik}).

$$SR_{ij} = \sum_{i}\sum_{k}\sum_{m} P_{ij} \left(\sum_{o} RF_{ko} A_{ko} R_{ko}\right) D_{jkm} F_{ik} , \qquad (1)$$

where

SR_{ij} = state unit-risk (person-rem/km) for shipping the source term through population zone j in state i;

P_{ij} = accident probability/km in state i in population zone j,

RF_{ko} = fraction of isotope k released in accident severity category o,

A_{ko} = fraction of released isotope k in aerosolized form in accident severity category o,

R_{ko} = fraction of aerosolized isotope k in respirable form in accident severity category o,

D_{jkm} = dose (person-rem) from isotope k from pathway m in population zone j, and

F_{ik} = food transfer factor for isotope k in state i equals 1 for pathways other than ingestion.

The isotopic unit-consequence factors are generated by using the RADTRAN 4 code. The unit-consequence for each isotope is broken down by pathway as calculated by RADTRAN 4. Groundshine, inhalation, resuspension, cloudshine, and ingestion pathways are generated by using the following input:

1. 1 Ci of each isotope present in the shipment,
2. 1 km traveled in each population zone,
3. Accident probability of 1/km for each population zone,
4. Population density of 1 person/km^2 in each population zone,
5. Release and dispersion in a completely aerosolized form of all the isotope after an accident, and
6. Complete transfer of all the radionuclide from the land to the food ingested (food transfer factor = 1)

Thus, the same unit-consequence factors can be used in concert with different amounts of the isotope, population densities, distances, accident probabilities, and package characteristics. By developing unit-consequence factors by isotope with RADTRAN 4, use of the unit-consequence factors is not restricted to only one source term such as source term Z, but rather can be used individually as the need arises for any source term since the factors are specific to a unit amount of a particular radionuclide.

Source Terms

Approximately 140 isotopes are currently in the isotope database. Only three RADTRAN 4 runs are necessary to generate all the isotopic unit-consequence factors. RADTRAN 4 can only accommodate 65 radionuclides at one time, but the values for truck and rail are the same, and there are no distinctions among population zones for accidents except among those variables already taken into consideration in Eq. 1 such as mileage, accident rates, and population density. If one or more of radionuclides 1-5 are not in the isotope database, the necessary unit-consequence factor(s) can be generated with one run of RADTRAN 4. Therefore, the use of isotopic unit-consequence factors allows us to develop a source term database with minimal effort.

At present, source terms that include high-level waste, SNF, transuranic waste, low-level waste, low-level mixed waste, and greater-than-Class C waste are available. Each source term is associated with a parameter file that contains the package characteristics, size and external dose rate for incident-free calculations, and release fractions for accident risk calculations. Parameter files are not necessarily specific to a given source term but rather to package type and can also be developed separately in some cases. An example would be the release characteristics of a TRUPACT-II container for transporting transuranic waste. The characteristics would be expected to be fairly uniform over a fairly wide range of waste composition. If source term Z is not in the database, its name and associated radionuclide inventory file and parameter file names can simply be added to a master source term list. The source term file for Z would have radionuclides 1-5 listed along with their amounts in Ci.

Routes

Route-specific information, such as the distance traveled and population densities along the route, are readily input into a database on a route-by-route basis from information obtained from the HIGHWAY routing code for truck transport (4) or the INTERLINE routing code for rail transport (5). A database of approximately 800 + routes each for truck and rail transport among 30 + DOE sites currently exists. If the route from Site 1 to Site 2 is not yet available, files generated by HIGHWAY and INTERLINE for the route will be put in the database.

User Interface

We have developed a postprocessor of the unit-consequence factors in the transportation model on an IBM-compatible computer running under DOS. The postprocessor allows menu selection of multiple site/origin destination pairs, source terms, and the number of shipments by truck and rail. The results are presented in tabular form and summarize the impacts for each shipment and the entire shipping campaign. The impacts estimated are the dose consequences (incident-free) or risk (accident) and the attendant health risks, that is, cancer incidence, cancer fatalities, and genetic effects. These health risks are based on the ICRP 60 (6) suggested risk coefficients for induced cancer cases per person-rem, fatal cancer cases per person-rem, and genetic effects per person-rem, respectively. Two other nonradiological impacts are also estimated: the actual fatality risk directly related to traffic deaths and cancer deaths related to the emission of diesel exhaust in urban areas.

To run our sample case, the appropriate input and output file names should be set first through menu options so that the input selections made can be saved in the input file and so that no other files will be overwritten by the output file. Source term Z can then be selected from a pop-up list with the origin site as Site 1 and the destination site as Site 2. Origin/destination pairs can be selected from a site list, and the number of truck and rail shipments to be assessed are user defined in the appropriate edit fields. Once identified as a route to be used, the program will check that the appropriate HIGHWAY and INTERLINE routes are available and will deny the route selection if the files are not present. The user may switch between adding routes to a selected source term or adding source terms to a selected route. Once all selections are made, the risks for the chosen unique shipments will be calculated on a shipment-by-shipment basis, and the final results for the selected shipping campaign will be written to the output file and presented on the user screen.

The postprocessor is limited only by the system memory (640 K in the main memory for DOS) in the number of routes and source terms chosen for a single shipping campaign. All arrays are dynamically allocated. For perspective, on a system with 550 K of memory available for programs, a shipping campaign involving up to approximately 50 routes and 7 source terms of about 20 radionuclides each can be evaluated in a single set of calculations. In summary, given a specific source term, waste package characteristics, and transportation route, the estimated risks can be calculated with a minimum of effort.

CONCLUSIONS

The use of unit-consequence factors has allowed us to develop an easy to use menu-driven program for analyzing the transportation risk of radioactive material for large shipping campaigns. The most up-to-date and detailed route-specific information possible is used. Input data need only be checked and verified once for each possible route and for each source term before any shipments are chosen for analysis. Separate input files (and therefore separate output files) are not required for each source term shipped over a specific route, thus alleviating the need for large amounts of storage space and complicated tracking procedures. In addition to the above quality assurance benefits, the modular approach employed allows for the easy addition of new routes and source terms for analysis when necessary.

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