A DEMONSTRATION SENSITIVITY ANALYSIS FOR RADTRAN III*

P. C. Reardon, K. S. Neuhauser
Sandia National Laboratories**
Albuquerque, New Mexico 87185

ABSTRACT

RADTRAN III is a computer code for the assessment of transportation risk. It has been used to conduct risk analyses of radioactive material shipments for the DOE Office of Defense Programs, the DOE Office of Civilian Radioactive Waste Management (OCRWM), and others. These analyses require large amounts of data, and the values of the input parameters influence the magnitudes of the total risk estimates to varying extents. The degree of change in the output (risk) to changes in certain input parameter values is examined here for a sample problem from the OCRWM analyses. This paper demonstrates the sensitivity of risk estimates generated by RADTRAN III for a sample problem. Parameters contributing to incident-free and accident risk were analyzed.

INTRODUCTION

The RADTRAN III computer code for transportation risk assessment (1) has been used to conduct radiological risk analyses for the DOE Office of Defense Programs, the DOE Office of Civilian Radioactive Waste Management, and others. The code addresses both incident-free and accident cases for all transport modes, and has been used to evaluate risk for shipments of such diverse materials as radiopharmaceuticals, plutonium oxide, transuranic defense wastes, and spent fuel from commercial power and foreign research reactors. RADTRAN III requires large amounts of input data. The values of some input parameters may have significant associated uncertainties. In such cases, conservative upper-bound values are usually used so that one may have high confidence that the actual risk is unlikely to exceed the resulting estimates. For a particular application, such as spent fuel transport, project-specific values may be developed and assigned to the relevant RADTRAN input parameters. Package testing programs, for example, have yielded a great deal of such data in the 10 years since RADTRAN was first developed. In addition, improvements in the RADTRAN models themselves have increased the need for data refinement. As a result risk estimates tend to decrease in magnitude with successive analyses as conservative default values are replaced with project-specific information. The relative significance of these parameters is discussed in this paper for a sample problem, the transport of spent fuel by truck. In this analysis, sensitivity is defined as the degree of change in output when the input deviates from that used in the base case. The base case values for the sample problem are those used in the transport risk analysis for the OCRWM EAs.

The sample problem was taken from the full set of reactor-to-repository routes in the risk analysis conducted for the Final Environmental Assessments (EAs) for the candidate first repository sites proposed by the DOE's Office of Civilian Radioactive Waste Management (OCRWM) (2). The sample problem represents 576 truck shipments of spent fuel from the Crystal River reactor in Florida to the candidate repository site near Hanford, WA. The number of shipments represents the spent fuel assemblies expected to be shipped to the first repository from this reactor. The one-way distance is 4817 km, one of the longest routes in the data set. The population distribution along this route is nationally representative, and the route crosses a maximum number of states. One could traverse more states, but only by less direct routes. Each shipment consists of 1 5-year-old PWR spent fuel assembly in a legal-weight truck cask. The route uses the Inter- state Highway System, consistent with DOT regulations as generated by the routing code HIGHWAY (3).

The analysis addresses variations in mean values over the entire sample-problem route. This is not the same as a segment-by-segment analysis. In the latter, risk for a particular segment of highway may be large, for example, because it has an accident rate much larger then either the national average or the range of accident rate variation studied in the present analysis. The risk per kilometer of travel is multiplied by the travel distance to obtain total risk for the segment. Thus, the contribution to overall trip risk from such a segment typically would be expected to be small since such high accident rate segments are usually short. Further, the presence along a route of short segments with high accident rates would be unlikely to raise the average accident rate for the entire route by a factor of 2 above the national average, which is the largest change examined in this study. In that sense the present analysis is a bounding study, but it does not address specific risks associated with travel along specific segments of the route that may have high accident rates, high population densities, or other distinctive attributes.

RESULTS

Sensitivity to Incident-Free Parameters

In RADTRAN III, incident-free and accident risk are calculated separately, and they are addressed separately in this analysis. For incident-free risk 37 parameters entering into this calculation were analyzed. They are listed in Table I. Techniques from differential calculus and error analysis were applied to define uncertainties. This is possible because the equations relating output to input are linear and input values are reasonably well known. The parameters were ranked by their Importance Value,

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of the longest routes in the data set.

TABLE I

Incident-Free Importance Analysis Summary

Importance value indicates the change (in person-rem in the risk from a 1% change in the parameter.

Description of Parameter	**Importance**
K ZERO	**6.50E+00**
TRANSPORTATION INDEX	**6.51E+00**
PACKAGES PER SHIPMENT	**6.50E+00**
DISTANCE TRAVELED	**1.99E+00**
SHIPMENTS PER YEAR	**6.50E+00**
POPULATION-RURAL	**4.41E-03**
POPULATION-SUBURBAN	**2.45E-01**
POPULATION-URBAN	**1.00E-02**
FRACTION OF TRAVEL IN RURAL ZONE	**6.86E-01**
FRACTION OF TRAVEL IN SUBURBAN ZONE	**7.98E-01**
FRACTION OF TRAVEL IN URBAN ZONE	**8.88E-03**
FRACTION OF TRAVEL ON FREEWAYS	**-4.87E-01**
FRACTION OF TRAVEL ON CITY STREETS	**3.25E-03**
FRACTION OF URBAN RUSH HOUR TRAVEL	**1.35E-01**
VELOCITY-RURAL	**-8.03E-01**
VELOCITY-SUBURBAN	**-1.07E-00**
VELOCITY-URBAN	**-1.11E-02**
RURAL TRAFFIC COUNT	**7.78E-02**
SURBURBAN TRAFFIC COUNT	**2.35E-01**
URBAN TRAFFIC COUNT	**5.54E-03**
SUBURBAN SHIELDING FACTOR	**2.03E-01**
URBAN SHIELDING FACTOR	**3.00E-04**
RATIO OF PEDESTRIAN DENSITY	**4.40E-02**
PERSONS EXPOSED WHILE STOPPED	**4.51E+00**
EXPOSURE DISTANCE WHILE STOPPED	**-9.02E+00**
STOP TIME	**4.51E+00**
NUMBER OF PERSONS EXPOSED DURING STORAGE	**.00E+00** *
STORAGE EXPOSURE DISTANCE	**.00E+00** *
STORAGE TIME PER SHIPMENT	**.00E+00** *
DISTANCE FROM SOURCE TO CREW	**-1.84E+00**
NUMBER OF CREW MEMBERS	**9.21E-01**
NUMBER OF FLIGHT ATTENDANTS	**.00E+00** *
NUMBER OF PEOPLE PER VEHICLE	**8.19E-01**
PERSONS EXPOSED PER HANDLING	**.00E+00** *
HANDLER EXPOSURE DISTANCE	**.00E+00** *
EXPOSURE TIME FOR HANDLERS	**.00E+00** *
NUMBER OF HANDLINGS	**.00E+00** *

* A zero indicates that parameter did not influence the calculation.

a measure of sensitivity that indicates the influence on the output resulting from a 1% change in the value of the given parameter.

Table I provides a measure of the relative importance to the total incident-free dose of variations in each parameter. The six input parameters having the most influence on the magnitude of the incident-free risk for the sample problem are the exposure distance at stops, the dose rate conversion factor K_0, the Transport Index, the number of packages per shipment, the number of shipments per year, and the distance traveled. A 1% increase in exposure distance at stops for example decreases risk to the general public by about 9 person-rem or about 2.5%. For most of the remaining parameters the effect of a 1% change is much less than 1 person-rem (less than 1%).

Accident Sensitivity Results

For accident risk four parameter groups were studied: fractions of travel, accident rates, severity fractions, and release fractions. The base case values are given in Table II. Monte Carlo-like methods were used because of the presence of nonlinear dependencies in release and dose-response relationships and because an artificially wide range of parameter variation is possible for factors associated with accident risk. In addition, such large variations were treated because accident risk estimates are of public concern. Changes of 100% (a factor of 2) were examined for the more firmly established input parameters, and variations ranging over two orders of magnitude around the base case values were taken for others. For each parameter group and the combined case, the parameters were allowed to vary randomly within the prescribed limits for 1000 iterations of the RADTRAN III calculation. The output (risk estimates) were accumulated into 30 intervals centered around the base case value. The results are presented as bar graphs showing the frequencies with which the output values fell into each interval.

TABLE II

Base Case Values for Accident Risk Parameters
(Base Case Accident Risk = 2.34 person-rem)

PARAMETER	**BASE CASE VALUE**
Rural Travel Fraction	**0.8059**
Suburban Travel Fraction	**0.1915**
Urban Travel Fraction	**0.0015**
Rural Accident Rate	**1.4E-7 acc/km**
Suburban Accident Rate	**3.0E-5 acc/km**
Urban Accident Rate	**1.6E-5 acc/km**
Rural Acc. Occurrence Fraction*	**(Fractions for Categories 1-6)** **0.603; 0.394; 3.0E-3;** **3.0E-6; 5.0E-6; 7.0E-6**
Suburb. Acc. Occurrence Fraction	**0.602; 0.394; 4.0E-3** **4.0E-6; 3.0E-6; 2.0E-6**
Urban Acc. Occurrence Fraction	**0.604; 0.395; 3.8E-4** **3.8E-7; 2.5E-7; 1.3E-7**
Release Fraction*	**(Fractions for Categories 3-6):**
Crud (Cobalt-60)	**0.12; 0.12; 0.12; 0.12**
Noble Gases (Krypton-85)	**0.00; 0.01, 0.10, 0.11**
Cesium Isotopes	**0.00; 1.0E-8; 2.0E-4;** **2.8E-4**
Eu,Sr,Am,Ce,Pu	**0.00; 1.0E-8; 5.0E-8;** **5.0E-8**
Ruthenium	**0.00; 1.0E-8; 1.0E-6;** **4.2E-5**

* **This represents the probability, given that an accident has occurred, of the accident being of a specific severity.**

** **No release is possible in Categories 1 and 2. Sensitivity to Fractions of Travel**

The fractions of travel in the three population density zones must be treated as a group because their sum must equal 1.0. Since consequences associated with urban and suburban travel are potentially higher than those associated with rural travel, the fractions of travel in urban and suburban zones were individually varied. The fraction of urban travel was allowed to assume values between 0 and 5%, and the fraction of suburban travel was allowed to assumed values between 5% and 25%. In both cases all values were specified to be equally probable. The fraction of travel in rural zones was set equal to the remainder (i.e. to between 95% and 70%). The limits of variation for urban and suburban travel fractions were taken from the full set of routes from all reactors to all candidate repository sites given in the OCRWM EA transportation risk analysis. Fig. 1 shows that the results lie in the narrow region between 0.55 and 3.5 person-rem. The risk values generated in this parameter analysis suggest that choosing alternate routes on the basis of fractions of travel would result in limited changes in general population exposures.

Sensitivity to Accident Rates

The accident rate variable is assigned a distinct value in each population density zone in order to reflect the differing incidence of accidents in rural, suburban, and urban areas. These accident rate values were derived from historical accident data, and a relatively high level of confidence can be placed in them. Therefore, each was allowed to vary by a factor of 2 around the base case value. That is, the accident rates were allowed to assume values as low as 1/2 of the base case value and as high as 2 times the base case value, with all values equally probable. As shown in Fig. 2, the values lie in a narrow region between 0.9 and 4.5 person-rem, centered around the base case value of 2.34 person-rem. Again, these results suggest that changes in accident rates would have little effect on population exposure.

Sensitivity to Accident Severity Fractions

The basic accident probability in each population density zone may be partitioned into a maximum of eight subdivisions (the Accident Severity Category matrix) to account for the fact that accidents vary widely in severity. For spent fuel transport, the range of all accidents was divided into six categories. Note that using less than the maximum number of categories available does not mean that accidents have been omitted, merely that the full range of accidents has been divided into six groups for this application. The sum of the frequencies still equals 1.0. Categories 1 and 2 represent accidents equivalent to the Type A and Type B packaging standards, respectively. Category 3 represents a "crud release" scenario which involves impact forces greater than the Type B standard, which are sufficent to damage cask seals, but not sufficient to damage the fuel elements. Only particulate crud on the external surfaces of the fuel elements is available for release in this scenario. Category 4 represents impact accidents without fire that are severe enough to damage the fuel elements, allowing crud release and also release of some of the gaseous or volatile radionuclides in the fuel elements. Categories 5 and 6 represent crud release and fuel pin damage from impact and also an increasingly severe fire. As a result, in Category 5 thermal rupture occurs (800C for more than 30 minutes), and in Category 6 fuel oxidation occurs. Categories 3-6 are the so-called "extraregulatory" severity categories. The probabilities of these accidents are so low that the values assigned to them are extrapolations from historical accident data. Because of the uncertainty inherent in such an approach and because of a desire to bound the risks of such events, the values assigned are highly conservative. Thus, the base case values for this parameter group are already likely to be overestimates of the actual probabilities.

Severity Category 3 has relatively narrow upper and lower bounds: a significantly lower impact would be a Category 2 accident and a significantly greater impact would be a Category 4 accident. Thus, the probability of a Category 3 accident was assumed to be normally distributed with a mean equal to the base case value. Values within a factor of 3.99 above and below the mean were randomly selected by the computer with the constraint that values less than zero were omitted to avoid negative probabilities. Similarly, the remaining categories were allowed to vary over a factor of 10 above and below the base values. That is, values as low as 1/10 of the base case value and as high as 10 times the base case value were permitted, with all values being equally probable.

The results are as shown in Fig. 3; the values lie between 1 and 15 person-rem. The asymmetry is

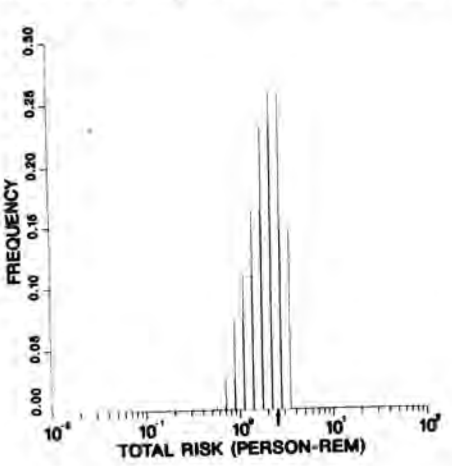

Fig. 1. Accident Sensitivity to Travel Fraction Changes.

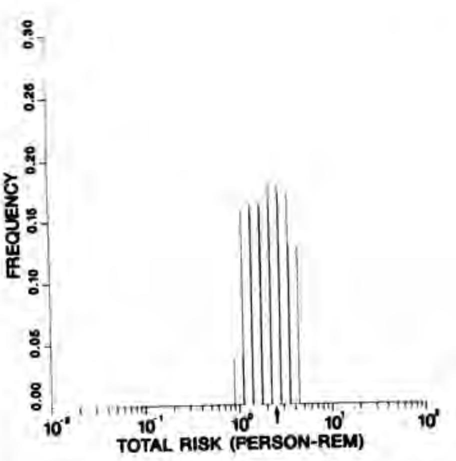

Fig. 2. Accident Sensitivity to Accident Rate Changes.

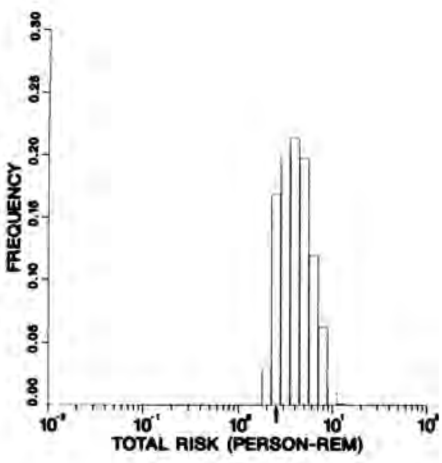

Fig. 3. Accident Sensitivity to Severity Fraction Changes.

attributed mainly to the truncation of the Category 3 values at 0 to avoid negative probabilities. It should be noted that although parameters for Categories 4-5 were allowed to vary over wider ranges, Category 3 still influences the results because it remains the most probable "extra-regulatory" accident category.

Sensitivity to Release Fractions

A release fraction is assigned to each radionuclide group for each severity category for each packaging type. This parameter represents the fraction of total package contents, by radionuclide group, that may be released from the package in a given severity of accident. The values are zero for Categories 1 and 2 (No Type B package failures are expected to occur nor have any ever occurred in accidents of these severities, because of the Type B package qualification tests.). Base case parameter values used for Categories 3-5 for spent fuel casks are derived from test data and conservative engineering judgement. Since the uncertainty associated with this parameter group may be large, distributions were again allowed to vary by a Factor of 10 above and below the base case values as they were for the severity category parameters. As before, all values within these limits were equally probable.

The majority (90%) of the output values lie in the range between 0.4 and 18 person-rem. The results (Fig, 4) are not as closely clustered as they are for the other parameters studied. This reflects the greater uncertainty associated with this parameter group.

Sensitivity to Combined Variation

To examine the combined influence of all four parameter groups on the output, all were allowed to vary simultaneously during 1000 RADTRAN runs. The *output* was accumulated in 30 intervals centered around the base case value as described above. As shown in Fig. 5, the resulting distribution remains somewhat flat over most of its range, mainly as a result of the release fraction influence. The quick *tailing off* reflects the low likelihood of all parameters simultaneously assuming either very high high or very low values. The result is that dose values between 0.9 and 18 person-rem are about equally probable; outside this range the likelihood of obtaining a risk estimate that is either higher or lower decreases rapidly.

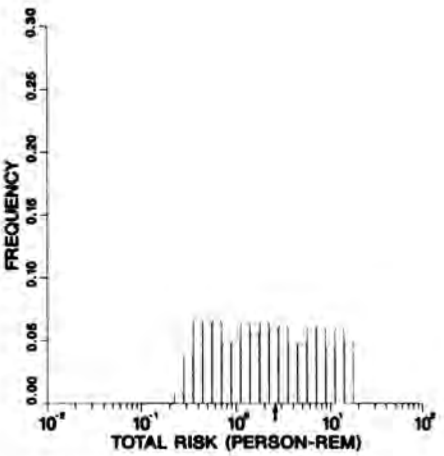

Fig. 4. Accident Sensitivity to Release Fraction Changes.

Probability-Consequence Envelope

An alternative way of examining risk is through probability-consequence curves. Such a curve shows the consequence of an accident plotted against the probability of achieving that consequence or one that is smaller. Thus, the curve shows the range of accident consequences in concert with their probabilities rather than as the probability times consequence products of which total risk is the sum. Thus, the consequences are not "masked" by low probabilities of occurrence. The probability-consequence curve for the base case is shown in Figure 5 as the solid line. The dashed lines bound the maximum and minimum probabilities which result at each dose level from the combined variation of the four parameter groups. The upper bound is between 1 and 2 orders of magnitude above the base case, and the lower bound is between 2 and 3 orders of magnitude less than the base case values.

CONCLUSION

Importance ranking of the parameters contributing to incident-free risk of truck transport of spent fuel shows that the six most important parameters are the exposure distance at stops, the dose rate conversion factor K_0, the Transport Index, the number of packages per shipment, the number of shipments per year, and the distance traveled. Of these, the first is most easily controlled or varied for spent fuel shipments.

The RADTRAN III accident model shows a high degree of stability; that is, a change in an accident parameter typically produces a change in the total accident risk that is smaller than the magnitude of the parameter change. For accident consequences to be severe a number of independent events must occur simultaneously, and some of those events have low probabilities of occurrence. It is logical that no single parameter should dominate accident risk. Thus, the stability of RADTRAN III, as demonstrated in this analysis, provides an independent comfirmation of the validity of the RADTRAN III accident model.

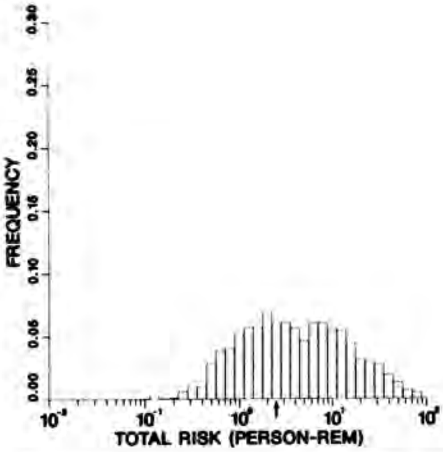

Fig. 5. Accident Sensitivity to Combined Changes.

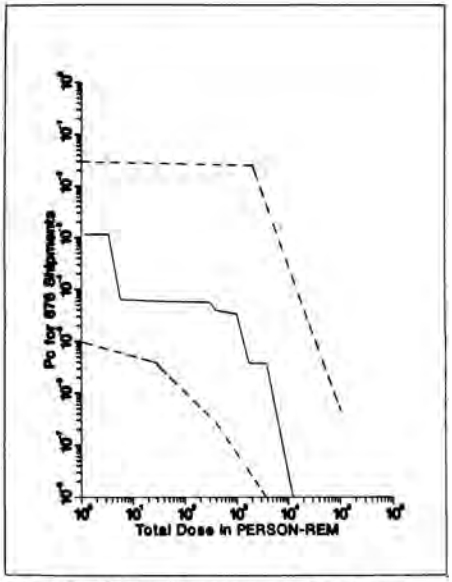

Fig. 6. Probability-Consequence Envelope.

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