ADROIT: A New Model for Analyzing Risk Associated With Transportation of Nuclear Explosives and Nuclear Materials*

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INTRODUCTION

The U.S. Department of Energy ships nuclear explosives, nuclear components, and other special nuclear material in support of Defense Programs activities. The primary mode of transportation is over public highways by the Armored Tractor/Safe-Secure Trailer (AT/SST) combination, which was designed and equipped specifically for this mission. This paper describes a new computer code, ADROIT (Analysis of Dispersal Risk Occurring in Transportation), which is the principal tool used in assessing the risk of Defense Programs transportation operations. The emphasis of the discussion in this paper is on information support and methodology. Recent applications of the code are also discussed briefly.

THE ADROIT CODE

ADROIT was originally developed at Sandia National Laboratories for the Defense Programs Transportation Risk Assessment (DPTRA) study, which was completed in September 1994. The current version of ADROIT evaluates risk associated with (1) dispersal of radioactive material resulting from a severe accident (the accident dispersal risk), (2) intrinsic radiation from the cargo, which exposes the public to very low levels of ionizing radiation during normal truck transportation (the incident-free risk); and (3) blunt trauma and/or burns resulting from the direct effects of a truck accident (the accident fatality risk). Each of these risk metrics are discussed in subsequent sections of this paper. The results of ADROIT are transporter-, package-, and route-specific.

ADROIT incorporates several enhancements relative to previous risk assessment models for hazardous materials transportation, including newly developed and updated statistics on the probabilities and severities of tractor semi-trailer accidents; test data and engineering models that are used to assess the response of the AT/SST and its cargo to

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the accident environment; and detailed route characterization using the 1990 Census data, which is used to assess accident rates, probabilities of different meteorological conditions, and population exposure. The block population data from the 1990 Census are used directly (as opposed to population densities) to calculate dose exposures. ADROIT includes a comprehensive treatment of uncertainty in the input parameters and the results based on the Latin-Hypercube sampling technique.

INFORMATION SUPPORT

An extensive set of databases are used in conjunction with ADROIT, including but not limited to the following:

- GES (General Estimates System), TIFA (Trucks Involved in Fatal Accidents), and TIFA supplemental data (gathered from police reports and interviews of those involved, witnesses, and responders) are used to calculate accident rates and the statistics of the types and severities of accidents (Clauss et al. 1994). These data sources were developed specifically for the DPTRA study and are more current and more detailed than other widely used sources of accident data (Clarke et al. 1976; Dennis et al. 1978; Fischer et al. 1987).
- Vehicle response thresholds and other vehicle data are used to characterize the response of the SST to accident environments, including collision, rollover, and fire. These data enable consideration of safety-related equipment in the AT/SST or other vehicles.
- Package response thresholds and other package data are used to characterize the response of the package to accident environments. These data provide for a package-specific analysis that considers the loading configuration, physical characteristics, and performance of the package of interest.
- The 1990 Census Tiger Line (Bureau of the Census 1991a and 1991b) files are used to develop route segmentation data files that contain information on the geographic location, type of roadway, population area, and most applicable meteorological station at closely spaced points.
- National Climatological Data Center (NCDC) upper air profiles are used to characterize meteorological conditions.
- 1990 Census population data (Census of Population and Housing 1991a and 1991b) are used to estimate population exposure based on the location and population count of all census blocks within the dispersal area.

ACCIDENT DISPERSAL RISK

The accident dispersal risk calculation in ADROIT is built upon three elements: <u>probabilities</u> of release and specific consequence scenarios developed from an event tree; <u>consequences</u> evaluated for each end event in the tree through an assessment that integrates the dispersal calculations, route characterization, population data, and dose-health effects models to provide estimates of excess latent cancer fatalities (LCFs); and <u>uncertainties</u>, evaluated by incorporating a Latin Hypercube Sampling scheme into the calculations for probabilities and consequences.

The event tree for the AT/SST accident dispersal probability analysis consists of 17 questions, as shown in Figure 1. The event tree is composed of answers to questions that define the types and severities of transportation accidents that occur, response of the packaging system (the packaging system includes the transport vehicle as well as the package and its contents), accident locations, and the meteorological conditions. Each question is used in all paths through the tree (scenarios), however, answers to some questions may not be used for all scenarios. The initiating events for the tree are traffic accidents in one of four operating environments. The operating environments are based on road type and population area. Although the structure of the tree is the same for all four initiating events, the quantification of some of the branches depends on the operating environment. The initiating events are quantified in terms of a probability per vehicle-trip. All other branches of the tree are quantified in terms of conditional probabilities.

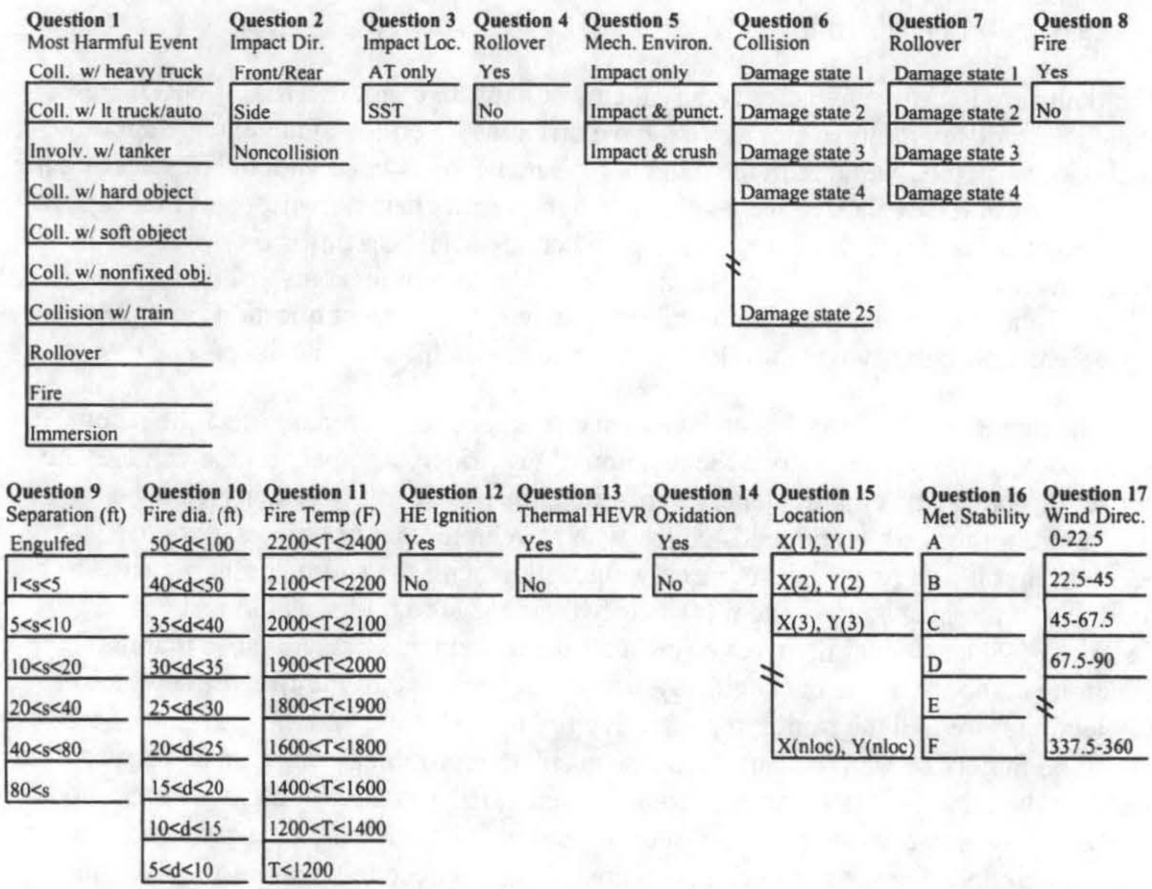


Figure 1: ADROIT event tree for truck accident dispersal probability

Highway transportation accidents are considered in four different operating environments based on road type and population area. Road types are divided into limited-access roads and non-limited-access roads. The distinction in road type is made because accident rates and the probability of different accident types vary significantly with road type. Population areas are divided into urban and rural areas. The distinction in population area was retained primarily to capture the difference in the size of the population exposed given a dispersal event. The initiating event probabilities reflect the accident rate per mile in each operating environment for the AT/SST (Phillips et al. 1994) and the average annual mileage for the hazardous cargo in the operating environment of interest. The mileage in each operating environment is derived from shipment projections and the route segmentation data files.

The branches of questions 1-14 define accident environments and the response of the packaging system to these environments. Transportation risk assessments typically consider impact, puncture, crush, and thermal environments. In tractor semi-trailer accidents, impact, puncture, and crush environments are associated with collision and rollover events; thermal environments are associated with fires involving the fuel system, cargo, or other elements of the vehicles and/or objects involved in the accident. The response of the packaging system to these environments is interdependent. For example, the response of the packaging system to a fire reflects damage to the packaging system caused by collision and rollover.

Accidents are initially characterized by the most harmful event (MHE). ADROIT uses the MHE to differentiate accidents that have different severities to the extent supported by the information available in the databases. The key factors considered in selecting the MHEs used in the event tree were vehicle weight, crush characteristics, and fuel capacity. Note that fires and rollover can occur even when the MHE is a collision event and collisions may occur when the MHE is fire, rollover, or immersion. Collisions, fire, rollover, and immersion are not mutually exclusive. Subsequent questions are used to evaluate the probability of multiple threats occurring in the same accident.

If the accident involves a collision, accident characteristics that may affect the response of the packaging system include the location of the principal impact on the vehicle, the impact direction, the collision energy absorbed, the peak contact velocity, and the collision duration, which depends on the type of vehicles and/or objects involved. If the accident involves a rollover, the primary characteristic of the rollover that may affect response of the packaging system (primarily by damage to trailer walls) is the skid distance. If the accident involves a fire, additional accident characteristics that may affect the response of the packaging system include the size of the fire, the separation between the fire and the trailer, the effective fire temperature, and the duration of the fire. The factors chosen to characterize an accident represent a compromise between the accident data that were available or could be generated and the complexity of the model used to analyze packaging system response. Detailed engineering data are almost never available to describe the accident environments experienced by vehicles involved in traffic accidents, and so relatively simple, approximate methods of analysis are typically used to represent the response.

Question 5 is used to define the type of mechanical environments to which the package may be subject. An impact environment exists for all scenarios in which a collision occurs. The probability that a puncture environment also exists depends on the existence of probes and the likelihood that they will be aligned in such a way as to cause damage. The probability that a crush environment also exists depends on the loading configuration of the cargo.

Question 6 addresses the damage to the packaging system associated with collision events. The damage states are hierarchical and are listed from the most severe to no significant damage. Damage states are characterized by conditions that could release hazardous material as well as those that could degrade the performance of the packaging system in fire environments.

Question 7 is used to define the damage to the packaging system from rollover. For the AT/SST, the maximum acceleration (or deceleration) generated in rollovers does not threaten the functionality of the cargo restraint system and therefore, the primary concern in a rollover event is the possibility of damage to the trailer walls.

The response of the packaging system to fire environments is addressed in Questions 12-14. For scenarios in which a fire occurs and the package contains a nuclear explosive, the probability of high explosive (HE) ignition is obtained by evaluating the probability that the fire duration is greater than the minimum fire duration for HE ignition, t^*, which depends on the cargo of interest, cargo damage, total wall damage, fire separation, fire size, and effective fire temperature. Since collision and rollover can occur in the same accident, the total wall damage is obtained from the combination of the wall damage from collision with that from rollover. The computer code MELTER was developed to calculate t^* (Larsen 1994). A schematic of the MELTER thermal model is illustrated in Figure 2.

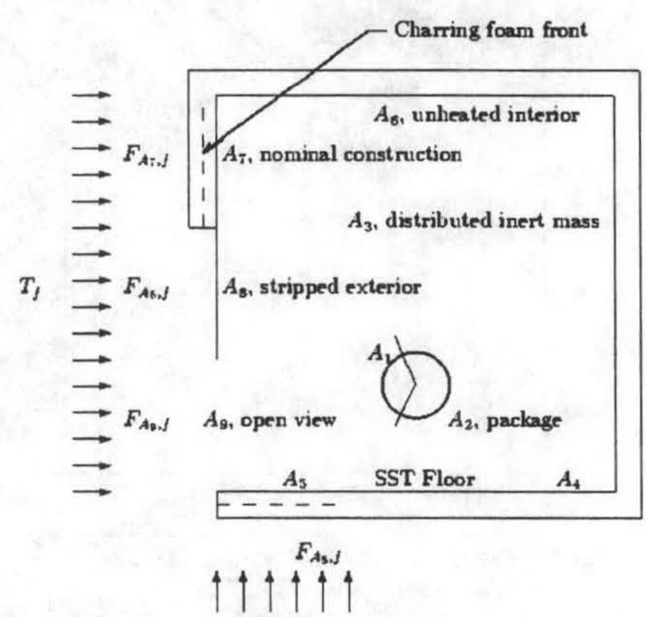
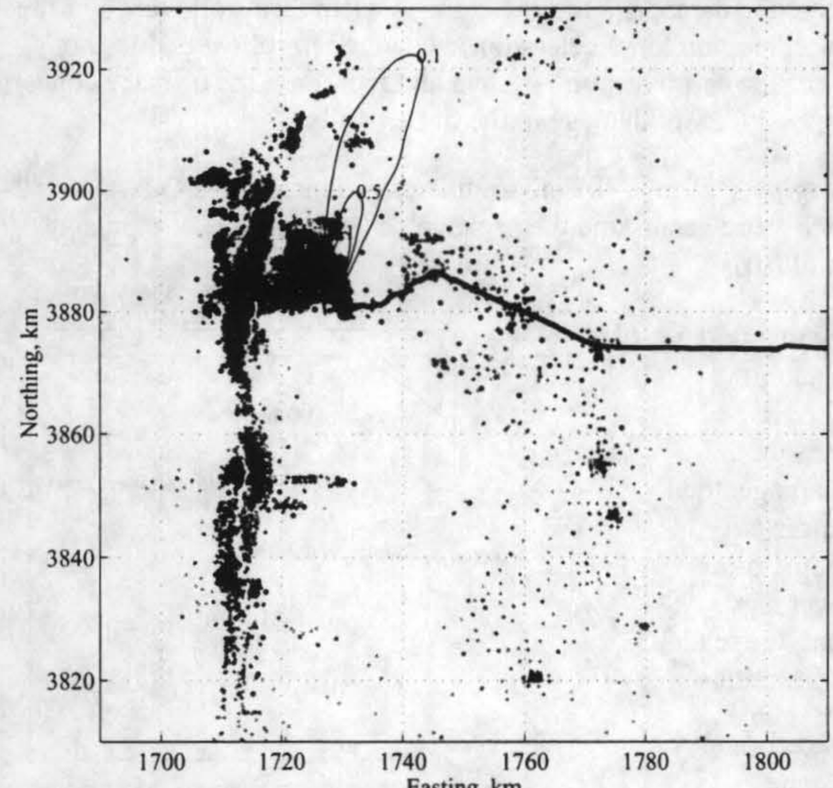


Figure 2: Schematic of MELTER thermal model

Question 13 is used to define the probability of a thermally initiated violent reaction of the HE given ignition. These estimates depend on the type of explosive and the heating rate. If a violent reaction of the HE does not occur, Question 14 is used to assess the probability that aerosol is generated by oxidation of the radioactive material. Detailed discussion of these questions is not included here.

Accident locations and corresponding meteorological conditions (Questions 15-17) are determined from route segmentation data files that were generated using the 1990 Census Tiger Line files.

Health consequences (LCFs) are determined from the product of the collective dose, the effective shielding factor, and a factor that converts dose to LCFs. The collective dose is obtained by summing the products of the number of people in each Census block and the dose at the internal block point, which is interpolated based on the results of a state-of-the-art dispersal assessment using the ERAD code (Boughton and DeLaurentis 1992), for all population blocks within the dispersal area. The effective shielding factor is based on analysis done for the NUREG-1150 study (Sprung et al. 1990). The factor used to convert dose to LCFs is obtained from BEIR V (BEIR V 1990). A separate consequence calculation is done for each unique consequence scenario identified in the probability analysis, which includes all combinations of dispersal mechanism, accident location, meteorological stability, and wind direction. The route segmentation data files are used to sample accident locations, provide a link with population data, and identify the appropriate meteorological conditions for the dispersal analysis. Environmental consequences (contaminated land area) are determined directly from the dispersal analysis. Figure 3 illustrates some of the elements of this process for a route originating in Albuquerque and proceeding east on Interstate 40.



Road Legend	Population Legend (Block Size)	Dispersal Legend
Limited/urban	0–10	Dose contours in rem
Limited/rural	10–100	
Other/urban	100–1000	
Other/rural	1000–10000	

Figure 3 Elements of ADROIT health consequence assessment

INCIDENT-FREE RISK AND ACCIDENT FATALITY RISK

The approach used in the incident-free risk calculations in ADROIT is based closely on that used in RADTRAN (Neuhauser and Kanipe 1993). ADROIT allows the user to input two different equivalent point source dose rates at 1 m from the center of the trailer--one appropriate for calculating the dose rate at the front of the trailer and one for calculating the dose rate through the sides of the trailer. ADROIT represents the location of people on the roadway and at rest stops with finer resolution than RADTRAN 4. Also, the off-road population density is route-specific and very finely discretized in the route segmentation files used with ADROIT. The accident fatality risk calculation is based on the tow-away accident rate for the AT/SST and on commercial tractor/semi-trailer accident experience. Data from the GES file for the years 1987-89 indicate that roughly 4.2% of tow-away accidents involve at least one fatality. Data from the TIFA file are used to evaluate the probability of x fatalities, where x is an integer.

APPLICATIONS

Since completion of the DPTRA study, ADROIT has been used to conduct calculations for the Over the Road Transportation Nuclear Explosive Safety Study Input Document, a Transportation Safety Analysis Report for the USDOE Transportation Safeguards Division, the Pantex Sitewide EIS (USDOE 1995), and other facility NEPA reports.

Figure 4 shows typical accident dispersal risk curves for transportation of nuclear explosives, as computed for the Pantex Sitewide EIS. The risk curve is a graph that displays the annual exceedance probability as a function of health effects (in this case, LCFs associated with accident dispersal). The shape of each curve reflects natural statistical variation (randomness) in the results, whereas the differences between the 5th, median, and 95th percentile curves reflect uncertainty in the results. The curves represent the annual probability, y, that the consequences are greater than or equal to the number of LCFs, x. For example, for the 95th percentile median curve, there is a probability of about $7x10^{-9}$ of an accident resulting in 10 or more LCFs and a probability of $5x10^{-7}$ of a an accident resulting in 1 or more LCFs.

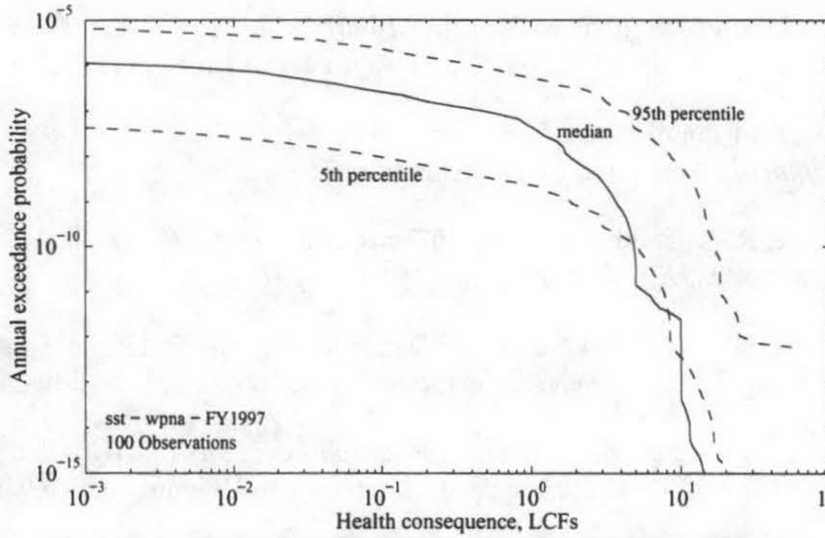


Figure 4: Accident dispersal risk curve from ADROIT

CLOSURE

ADROIT calculates accident dispersal, incident-free and accident fatality risk per trip for a specific transport mode, cargo, and route. The results can be aggregated on an annual basis (or any other fixed period of time) using postprocessing utilities. ADROIT can be modified to model the risk associated with other vehicles, cargoes, and dispersal mechanisms by incorporating other phenomenological and engineering models associated with the transport vehicle and cargo.

REFERENCES

BEIR V *Health Effects of Exposures to Low Levels of Ionizing Radiation: BEIR V*, Committee on the Biological Effects of Ionizing Radiations, Board on Radiation Effects Research, Commission on Life Sciences, National Research Council, National Academy Press, Washington, D. C. (1990).

Boughton, B. A. and DeLaurentis, J. M. *Description and Validation of ERAD: An Atmospheric Dispersion Model for High Explosive Detonations*, SAND92-2069, Sandia National Laboratories (1992).

Bureau of the Census *TIGER/Line Census Files, 1990* [machine-readable data files], Washington: The Bureau (1991a).

Bureau of the Census *TIGER/Line Census Files, 1990 Technical Documentation*, Washington: The Bureau (1991b).

Census of Population and Housing *1990: Public Law (P.L.) 94-171 Data on CD-ROM* [machine-readable data files], Washington: The Bureau (1991a).

Census of Population and Housing *1990: Public Law (P.L.) 94-171 Data on CD-ROM Technical Documentation*, Washington: The Bureau (1991b).

Clarke, R. K., et al. *Severities of Transportation Accidents*, SLA-74-0001, Sandia Laboratories, Albuquerque, New Mexico (1976).

Clauss, D. B., et al. *A Statistical Description of the Types and Severities of Accidents Involving Tractor Semi-Trailers*, SAND93-2580, Sandia National Laboratories (1994).

Dennis, et al. *Severities of Transportation Accidents Involving Large Packages*, SAND77-0001, Sandia National Laboratories, Albuquerque, New Mexico (1978).

Fischer, L. E., et al. *Shipping Container Response to Severe Highway and Railway Accident Conditions*, NUREG/CR-4829, UCID-20733, Lawrence Livermore National Laboratories (1987).

Larsen, M. E. *MELTER: A Model of the Thermal Response of Cargoes Transported in the Safe-Secure Trailer Subject to Fire Environments for Risk Assessment Applications*, SAND93-0737, Sandia National Laboratories (1994).

Neuhauser, K. S. and Kanipe, F. L. *RADTRAN 4 Volume II: Technical Manual*, SAND89-2370, Sandia National Laboratories (1993).

Phillips, J. S., et al. *Determination of Influence Factors and Accident Rates for the Armored Tractor/Safe Secure Trailer*, SAND93-0111, Sandia National Laboratories (1994).

Sprung, J. L., et al. *Evaluation of Severe Accident Risks: Quantification of Major Input Parameters*, NUREG/CR-4551, Vol. 2, Part 7, Sandia National Laboratories (1990).

USDOE, *Draft Environmental Impact Statement for the Continued Operation of the Pantex Plant and Associated Storage of Nuclear Weapon Components*, DOE/EIS-0225, U.S. Department of Energy (1995).