STATE OF NEVADA
AGENCY FOR NUCLEAR PROJECTS/
NUCLEAR WASTE PROJECT OFFICE

NWPO-TN-006-90

Probabilistic Risk Assessment and Nuclear Waste Transportation: A Case Study of the Use of RADTRAN in the 1986 Environmental Assessment for Yucca Mountain

by

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December, 1990

The Nevada Agency for Nuclear Projects/Nuclear Waste Project Office (NWPO) was created by the Nevada Legislature to oversee federal high-level nuclear waste activities in the State. Since 1985, it has dealt largely with the U.S. Department of Energy's (DOE) siting of a high-level nuclear waste repository at Yucca Mountain in southern Nevada. As part of its oversight role, NWPO has contracted for studies designed to assess the transportation impacts of a repository.

This study was funded by DOE grant number DE-FG08-85-NV10461.

Exhibit 8

RADTRAN ANALYSIS

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EXECUTIVE SUMMARY*

Introduction

The analysis of the risks of transporting irradiated nuclear fuel to a federal repository, Appendix A of the DOE Environmental Assessment for Yucca Mountain (DOE84), is based on the RADTRAN model and input parameters. The RADTRAN computer code calculates the radiation exposures and health effects under normal or incident-free transport, and over all credible accident conditions. The RADTRAN model also calculates the economic consequences of transportation accidents, though these costs were not included in the Department's Environmental Assessment for the proposed Yucca Mountain repository.

When the consequences of all credible accidents are combined with the probability of all credible accidents, the likely risk of transporting spent fuel to a repository, in terms of the potential number of health effects and the dollar cost per year, is calculated. To estimate health effects and economic costs due to the release of radioactivity in a radiation-related transportation accident, one must know the amount of radioactivity released in accidents of varying severity, the distribution or dispersion of radioactivity from the accident scene, the number of persons inhaling or ingesting radioactivity downwind through all pathways, and the relation between radiation dose and health effects. RADTRAN III could be viewed as a simple set of formulas and parameters which model physical reality to obtain an estimate of health effects. But on closer examination, RADTRAN III incorporates a host of assumptions about human behavior and numerous socioeconomic and political assumptions which greatly affect the predicted number of health effects and economic costs. These modelling assumptions and parameters are discussed in this report, along with a comparison of RADTRAN II and subsequent versions.

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* Drs. Anandalingham and Maarten DeKadt contributed to the analysis of probabilistic risk assessment, and sensitivity analysis, and insurance, respectively.

DOE84 *Draft Environmental Assessment Yucca Mountain Site*, *Nevada*, DOE/RW-0012, Washington, D.C., December 1984 and *Environmental Assessment*, *Yucca Mountain Site*, US Department of Energy, DOE/RW-0073, May 1986.

Incident-Free Transport

Spent fuel shipping containers are heavily shielded by uranium or lead in order to attenuate the X-ray and gamma radiation field. In addition, a neutron shield, consisting of an outer water jacket or boron neutron absorbers, attenuate the neutron field. The neutron field is due to spontaneous fission by transuranics in spent fuel, particularly curium-244. During normal, that is, incident-free transport, a gamma and neutron dose field exists outside the shipping cask, exposing pedestrians and residents, persons in vehicles along the transport link, drivers or train crew, and cask handlers, when the vehicle is moving or stopped, along highways and rail.

Under the prodding of states, the most significant change in RADTRAN II occurred in this non-accident component. RADTRAN III now includes a rail crew dose, an urban rail model, and a dose due to rail stops. In addition, RADTRAN III includes a dose to persons sharing the rail or highway transport link.

Nevertheless, the RADTRAN III model is still deficient in several respects. RADTRAN III does not include a neutron dose. This is important for train crew, handlers and all persons within 150 meters of the shipping cask. Within this distance, for a truck cask (NLI-1/2), gamma radiation is expected to provide 65% of the whole body dose, compared to 35% due to neutrons. For rail casks (IF-300), the percentage of the whole body dose due to neutrons could be as much as 50% (Park85). The relative neutron contribution is expected to be higher for the new larger capacity rail casks being considered by the Department of Energy. These percentages hold for incident-free conditions, where the wet neutron shield remains intact.

In an accident, whole body exposures to emergency personnel and crews due to a neutron dose will increase greatly over the dose estimated in RADTRAN III. Since the stainless steel outer liner of the neutron shield is only ¼ inch thick (Fischer87), it could be quite easily

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Park85 *Parametric Study of Radiation Dose Rates from Rail and Truck Spent Fuel Transport Casks*, Parks CV and OW Herman, ORNL/CSD/TM-227, Oak Ridge National Laboratory, August 1985.

Fischer87 *Shipping Container Response to Severe Highway and Rail Accident Conditions*, LE Fischer et al, NUREG/CR-4829, Lawrence Livermore National Laboratory, February 1987.

punctured in an accident. If the neutron shield tank is punctured, the neutron dose at the cask surface would increase by a factor of 35 (Park85).

In addition to this neutron dose, RADTRAN III does not include the entire dose due to gamma radiation. RADTRAN III includes only the direct gamma exposures. But an additional dose arises from reflection of gamma rays (Compton scattering) from the sky (skyscatter), and from the ground (groundscatter), the latter being more significant (Sandquist85). Groundscatter can contribute up to an additional 25% to the gamma dose (Sandquist85).

Finally, RADTRAN III assumes the cask is a point source of radiation rather than a line source. For distances far from the cask, this is not significant, but for rail and truck crews, this is an important consideration. The effective radiation dose to crews and persons sharing the transportation link is increased if the radioactivity is assumed to be distributed along the cask's axis rather than at a point.

Accident Severity/Release Fractions

The amount of radioactivity which can be potentially released from a cask or the release fraction is a function of the accident severity, among numerous additional considerations. In RADTRAN III, the accident severity categories range from I to VIII, though severe accident categories VII and VIII are excluded. This classification scheme has now changed in the Modal Study (Fischer87), and is expected to change in RADTRAN IV.

Fractional occurrences, that is, the fraction of the overall truck accident rate in each severity category, are compared for RADTRAN III and earlier studies. Without additional data, the percent of accidents in the less severe categories has increased in federal government-contracted studies between the years 1977 and 1983.

RADTRAN II used in the Environmental Assessments assumes that 99% of truck accidents take place in categories I and II, and that no severe accidents, categories VII and VIII occur. The worst case

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Sandquist85 *Exposures and Health Effects from Spent Fuel Transportation*, GM Sandquist, et al, RAE-8339/12-1, Rogers & Associates Engineering Corp, Salt Lake City, November 1985.

accident under category VI is a release of 1380 Ci. Category VII and VIII accidents involve a breach in the cask wall greater than 1 square inch. This exclusion leads to an underestimate of health effects and cleanup costs. The basis for the exclusion of categories VII and VIII in the Environmental Assessments is a consensus of experts at a workshop conducted by Sandia Lab's (Wilmot81). The panel eliminated high consequence events, categories VII and VIII, by taking into account the low probabilities.

This methodology is incorrect and based on a misunderstanding of probabilistic risk assessment. In a probabilistic risk assessment, the risk is obtained by summing over the <u>product</u> of probabilities and consequences for all events which are physically possible. To eliminate an event, one needs to critically examine the risk of the low probability, high consequence events to see whether it is in same risk envelope as high probability, low consequence events. Only if the <u>product</u> of consequence and probability is low, should the specific event be eliminated.

Probabilities, fractional releases and consequences can be greatly enhanced by human error and sabotage. Problems such as quality control, mishandling and organizational failures during loading and shipping are simply not factored into the RADTRAN III model and the Environmental Assessment. As Freudenburg has pointed out, the Three Mile Island and Chernobyl accidents were greatly enhanced by the complicated interaction between humans and machines (Freudenburg88). The response of emergency personnel during an accident would greatly affect the consequences.

This raises another issue, the quantifiable vs. the difficult to quantify accident scenarios. A probabilistic risk assessment must sum over all accident scenarios, else the absolute risk is underestimated. Human interactions with complex machines are difficult to quantify, but are critical in assessing consequences and probability (Freudenburg88). For example, a crack in a cask can lead to lead voiding in a fire. Human error can account for welding flaws. Or, performing a task

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Wilmot81 "Report on a Workshop on Transportation Accident Scenarios Involving Spent Fuel, May 6-8, 1980," EL Wilmot, JD McClure and RE Luna, Sandia National Laboratory, SAND80-2012, February 1981.

numerous times without incident can lead to declining levels of vigilance and increase the probability of an accident, such as occurred in the Valdez tanker accident (Freudenbur89). As another example, quantifying the pressure exerted by a realistically-shaped puncture object is an extremely complex problem which was not addressed by the Modal Study or RADTRAN III in determining fractional releases. These dynamic forces are difficult to quantify, but are crucial in determining whether the steel shell is actually pierced.

Whatever estimate of accident probability is arrived at needs to be supplemented by confidence levels. RADTRAN III does not clearly indicate where real data ends and expert opinion begins.

<u>Health Effects Model</u>

The health effects model and input parameters in RADTRAN III have not changed since the Rasmussen study (NRC75), though recent data suggest that a change in input parameters is warranted. Radiation doses in the model are due to gamma exposures and to ingestion and inhalation of radionuclides.

Given a direct exposure, RADTRAN assumes one latent cancer fatality for 10^4 person-rems whole body dose to the population. This latent cancer fatality rate is based on a 1965 study of Japanese bomb survivors by Oak Ridge National Laboratory. More recent data by (Preston87) and others suggest that the rate could be higher by a factor of 16 or more. Thus, the number of latent cancer fatalities assumed in RADTRAN III may need to be increased. This may change further following evaluation of Department of Energy nuclear worker data.

The actual radiation exposures expected during an accident depend critically on realistic accident scenarios. RADTRAN III assumes either a rural, suburban or urban population density, and calculates exposures due to inhalation of the passing radiation cloud or to direct exposures from deposited material. But a host of other factors, such as the accident dynamics, location, time of day, season, physical setting,

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NRC75 *Reactor Safety Study*, Appendix VI, WASH-1400, Nuclear Regulatory Commission, October 1975.
Preston87 "Reassessment of Atomic Bomb Radiation Dosimetry," DL Preston and DA Pierce, Radiation Effects Research Foundation, Technical Report 9-87, Hiroshima, 1987.

access routes, meteorology, precipitation, ventilation of buildings, and evacuation details, could play a crucial role in determining actual exposures.

Economic Parameters And Modeling Assumptions

To evaluate the reasonableness of clean-up assumptions, costs and RADTRAN's methodology, we evaluated one example in detail, the dispersal of radioactive materials from a severe spent fuel accident in an average rural area. We used the PATHRAE-T computer code (Sandquist85) to determine the ground concentrations, and then considered detailed decontamination of the rural area under 3 options of RADTRAN III. We then compared these 3 options with a two additional options, scraping a large land area and the cleanup of plutonium contamination in Palomares, Spain. Though we disagree that severe accidents, severity categories VII and VIII should be excluded, for the purposes of this discussion we assumed the fractional releases resulting from a category VI accident as postulated in the Yucca Mountain Environmental Assessment. Though larger casks could be employed in the future, the Environmental Assessment assumed that a rail cask contains 14 PWR fuel assemblies. To evaluate the economic assumptions and parameters in the RADTRAN III model, we considered only the gamma dose due to deposited radionuclides from an impact accident in which the fuel rods burst and uranium fuel is oxidized.

Under RADTRAN III, Option 1, all areas between 15 and 600 mr/y would be cleaned up; areas with dose greater than 600 mr/y would be interdicted. We assumed a cleanup criteria of 0.2 $\mu Ci/m^2$, the same as recommended by the Environmental Protection Agency for transuranic cleanup (EPA77). Under Option 2, the same area would be cleaned up, but the area with dose greater than 600 mr/y would be razed and rebuilt. Under Option 3, the entire area would be interdicted until the hazard was gone due to radioactive decay. Under this option, the area

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EPA77 *Proposed Guidance on Dose Limits for Persons Exposed to Transuranium Elements in the General Environment*, Environmental Protection Agency, EPA-510/4-77-016, 1977.

would be progressively resettled, as the radiation levels in each region decay to the criterion level, 15 mr/y.

The total decontamination costs, including replacing lost wages, lost crops, evacuation and security for options 1,2 and 3 are $176 million, $233 million, and $559 million, respectively. The times for cleanup or remediation for these three options were ten days, 470 days and 160 years, respectively. RADTRAN III would select the least expensive option, Option 1. It is important to note that RADTRAN III does not account for interest and inflation rates and does not determine costs in present-day dollars.

As an independent check on the three options, we assumed the region where whole body doses are ≥ 15 mr/y, is scraped to a depth of 10 cm and the contaminated earth is transported and buried. A range of clean-up costs can be postulated, depending on how the contaminated earth is packaged and "disposed of."

To scrape and bury an area where whole body doses are ≥ 15 mr/y to a depth of 10 cm, implies 11 million m^3 of contaminated earth, at a waste management cost of $330 million to $16.2 billion, the latter figure if the contaminated earth is classed as "low-level" waste. The enormous quantity of contaminated earth makes it likely that land would be interdicted. In addition to scraping earth, crops would be purchased, two radiation surveys would be conducted, evacuation and personal income loss compensated and buildings razed and reconstructed. The total costs in this fourth option would range from $464 million to $19.4 billion. Costs in the billion dollar range also result from scaling up costs in the Palomares, Spain cleanup. In contrast, the costs under Option 1 of RADTRAN III are $176 million. Costs could obviously vary by orders of magnitude depending on geographic location, property type and decontamination techniques used.

Many of these cleanup costs exceed coverage for the Department of Energy under the Price-Anderson Act, $500 million. Since the Department takes title to spent fuel in 1998, the $500 million limit applies. Our analysis of insurance underwriting practices leads us to conclude that, barring federal backing, private insurers are unlikely to insure high-level waste shipments.

For economic calculations, costs associated with litigation, government actions, indirect corporate losses and property devaluation are ignored. RADTRAN III does not properly take into account the indirect costs of a major contamination accident, just the direct costs such as crop purchases, and business and personal income loss. In a rural area, other businesses depend on farmers, such as seed companies, equipment suppliers, lumber and other suppliers, groceries and other retail businesses, such as clothiers. These indirect costs may more than double the direct losses (Bischak89). This is a major oversight which understates accident cleanup costs.

RADTRAN III also does not account for the economic cost of health effects, in terms of the loss of wages, the cost of hospital care, and other health-related costs.

The economic parameters for an urban clean-up are greatly revised upwards in RADTRAN III. Though this paper does not consider urban accidents, we note that the cost to raze and rebuild an urban area is now estimated to be \$3.6 billion/km^2. Under the same accident assumptions as above for a rural area, the cost to raze and rebuild an urban area alone is \$9.5 billion. The land value, assuming 10,000 persons/km^2, is now estimated to be \$6 billion. The time required to cleanup an urban area under RADTRAN III is almost four years. These estimated costs and cleanup times are probably low for New York City and other major densely populated cities, but probably high for most U.S cities. For an accident in an urban area, Price-Anderson insurance would pay back less than 10¢ on the dollar.

In contrast to RADTRAN II, there appears to have been some sensitivity analysis performed for vehicular accidents in RADTRAN III. It is mentioned that the problem "is far too complex to be amenable to a closed-form analytical treatment..." (Madsen86). Then, the RADTRAN III report provides some vague suggestions on how the problem can be rectified. We note that there are a number of Monte-Carlo techniques for estimating sensitivity in cases where closed form solutions are not

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Bischak89 "The Promise and Prospects for Economic Conversion of Ohio's Nuclear Weapons Facilities," G Bischak, Employment Research Associates, Lansing, Mich, May 1989.
Madsen86 *RADTRAN III*, Madsen MM et al, Sandia National Laboratory, SAND-84-0036, February 1986.

possible. Monte-Carlo simulations can be used to derive distributions of the impact vis-a-vis some parameter.

Sensitivity information in the case of vehicular accidents is particularly needed for the impact of the following variables: accident rates for all transportation modes in urban, suburban and rural settings, accident severity levels, percent and type of radionuclides released, meteorological assumptions, dilution factors and all the delay assumptions. We note that the RADTRAN model and the Environmental Assessment do not clearly specify when actual data or engineering estimates are employed as input parameters.

Conclusion

We conclude that the RADTRAN III model must be further improved to include a neutron dose and line source. A major disagreement remains regarding the inclusion of radiation releases from severe accidents, categories VII and VIII, and factoring human error and sabotage into the model. We recommend that the risk of category VII and VIII accidents be calculated to determine whether the effects would be small or large. While RADTRAN III now includes a food ingestion model, the health effects model must be updated to include the latest data on Japanese bomb survivors. Without these factors, RADTRAN III understates the health impacts of transporting high-level waste to the proposed Yucca Mountains repository.

Our calculation of the economic costs of cleanup of a rural area under RADTRAN III shows that the estimates can vary by a factor of 100 depending on the assumptions. The time for cleanup or interdiction could range from 10 days to 160 years. We regard the 10 day figure as unrealistically low. The social and political assumptions which underpin the RADTRAN III model must be carefully reconsidered. These costs are direct losses, not indirect losses or costs of cancers and illness which should be included. The health effects and economic costs can vary by orders of magnitude depending on the location of an accident. Under RADTRAN III, the costs of an accident in an urban area could be over ten times greater. The RADTRAN III model must be further refined to incorporate indirect economic costs in both rural and urban areas. The

Environmental Assessment must be revised to incorporate these economic costs for a cleanup. At a maximum of $500 million, coverage under the Price-Anderson Act is clearly inadequate. Congress must take another look at this matter.

GENERAL DISCUSSION*

The analysis of the risks of transporting irradiated nuclear fuel to a federal repository, Appendix A of the DOE Environmental Assessment for Yucca Mountain (DOE84), (DOE86), is based on the RADTRAN model and input parameters. The RADTRAN computer code calculates the radiation exposures and health effects under normal transport or incident-free conditions, and over all credible accident conditions. The RADTRAN model, based on an earlier model employed by the Nuclear Regulatory Commission for reactor accidents (NRC75) also calculates the economic consequences of transportation accidents, though these costs were not included in the Department's Environmental Assessment for the proposed Yucca Mountain repository.

When the consequences of all credible accidents are combined with the probability of all credible accidents, the likely risk of transporting spent fuel to a repository, in terms of the potential number of health effects and the dollar cost per year, is calculated. This risk depends on a host of modelling assumptions and parameters which are discussed in this report, along with a comparison of RADTRAN II and subsequent versions.

Though spent fuel shipping containers are shielded by lead or uranium and neutron absorbers, gamma rays and neutrons penetrate this shielding. Persons near the shipping cask, such as persons in cars, pedestrians and residents, transport crews and railway workers would receive a radiation dose under incident-free transport. RADTRAN III calculates the direct gamma radiation dose, though not the neutron component or the indirect gamma radiation dose due to photon reflection. These issues are also discussed in this report.

To estimate health effects and economic costs due to the release of radioactivity in a radiation-related transportation accident, one must know the amount of radioactivity released in accidents of varying severity, the distribution or dispersion of radioactivity from the

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accident scene, the number of persons inhaling or ingesting radioactivity downwind through all pathways, and the relation between radiation dose and health effects. RADTRAN III could be viewed as a simple set of formulas and parameters which model physical reality to obtain an estimate of health effects. But on closer examination, RADTRAN III incorporates a host of assumptions about human behavior and numerous socioeconomic and political assumptions which greatly affect the predicted number of health effects and economic costs. For example, exactly how many persons would actually inhale radioactivity in an accident in downtown Las Vegas? What should be the population density, the parameter used by RADTRAN III to estimate the number of persons receiving a radiation dose? This depends crucially on a realistic accident scenario. A typical accident scenario includes the curious, local police, fire and ambulance crews, traffic congestion and confusion. The number of persons who mass will depend on the time of day, season and accident location. The radiation dose due to inhalation will be a function of the proximity of persons to the accident, the duration of their stay, the physical setting, and the meteorology (wind speed, diffusion properties, precipitation). Accidents in different urban areas with the same population density could result in health effects orders of magnitude different.

Examined closer, RADTRAN III displays its roots - developed by physical scientists and engineers in a laboratory far removed from real people and the complexities of real life.

In an accident, the consequences are a function of the type and amount of radioactive material released from the shipping container (cask), the nature of the accident (fire, impact, and puncture), the meteorological conditions (diffusion; wet or dry deposition), the accident locale (urban, suburban, rural), human error and the response by emergency personnel.

The type and amount of radioactive material released in an accident depend on the nature and severity of an accident, the shipping mode, the strength of the cask, and the amount of radioactive material within each cask. In addition, the probabilities, fractional releases and consequences of an accident can be greatly enhanced by human error and sabotage. The latter factors were not taken into account in the Environmental Assessment.

The most difficult part of any risk assessment is constructing realistic accident scenarios and estimating realistic parameter values in a realistic model. Even simple factors like average shipment speed and population density are difficult to obtain. Other parameters such as the fractional release of radionuclides under variable impact speeds are frequently based on expert judgment which can vary widely. On such parameters as annual expected accidents of varying severity, there may be total disagreement. It is important for RADTRAN to be supplemented by the identification of all parameters that need to be estimated, and a methodology for arriving at some consensus on what parameter estimates should be used.

The health consequences depend on a health effects model developed in 1975 for reactor accidents (NRC75). Health effects in RADTRAN are evaluated for groundshine, cloudshine and inhalation [but not resuspension of radionuclides deposited on the ground, and in normal transport, reflection of gamma rays, and neutron dose]. External exposures are calculated by direct exposures to localized source, exposures to contaminated surfaces (groundshine), and penetrating radiation from the passing cloud (cloudshine). But have all radiation pathways been included and is there agreement on the dose/effect factor?

The economic costs and health effects also depend on a host of economic parameters and modelling assumptions, particularly, where the balance is struck on decontamination criteria, the <u>acceptable level of "cleanliness"</u>. What is acceptable is both a scientific issue and a political judgment. The public, through the political process, and state governments will play a large role. As an example, the additional health effects to the general public will be zero if each released radionuclide is recaptured and contained, though personnel exposures and economic costs for the federal government could thereby be maximized. On the other hand, the economic costs to the federal government will be minimized if no cleanup is conducted and residents remain and are exposed. These socioeconomic and political judgments are incorporated into the RADTRAN III model and are discussed at some length in this report.

The health effects due to inhalation of radioactive particles depend critically on realistic and credible accident scenarios. How does RADTRAN III accurately analyze the dynamics, location and physical setting of the accident scene and a host of other important factors?

For economic calculations, direct cleanup costs are included in RADTRAN III. Costs associated with litigation, government actions, indirect corporate losses and property devaluation are ignored. Costs can vary substantially depending on geographic location, property type and decontamination techniques used. RADTRAN III does not properly take into account the indirect costs of a major contamination accident, just the direct costs such as crop purchases, and business and personal income loss. These indirect costs may more than double the direct losses (Bischak89). This is a major oversight which understates accident cleanup costs.

RADTRAN III also does not account for the economic cost of health effects, in terms of the loss of wages, the cost of hospital care, and other health-related costs.

Though the RADTRAN model estimates both health effects and economic costs, only the potential health effects are included in the Department's Environmental Assessment. Since economic costs are automatically generated by RADTRAN, we believe the Department of Energy had to make a conscious decision to exclude this information from the Environmental Assessment.

This report attempts to address the above issues and to discuss the health and economic modelling assumptions and parameters in RADTRAN II and its later developments.

INCIDENT-FREE TRANSPORT

RADTRAN Method of Analysis

Spent fuel shipping containers are heavily shielded by uranium or lead in order to attenuate the X-ray and gamma radiation field. In addition, a neutron shield, consisting of an outer water jacket or boron neutron absorbers, attenuate the neutron field. The neutron field is due to spontaneous fission by transuranics in spent fuel, particularly curium-244. During normal, incident-free transport, a gamma and neutron dose field exists outside the shipping cask, exposing pedestrians, persons in vehicles along the transport link, drivers or train crew, and cask handlers, when the vehicle is moving or stopped, along highways and rail.

Under the prodding of states, the most significant change in RADTRAN II occurred in this incident-free component. RADTRAN III now includes a rail crew dose, an urban rail model, and a dose due to rail stops. In addition, RADTRAN III includes a dose to persons sharing the transport link.

The impacts of incident-free transport are incorporated in RADTRAN III parameters which specify the fraction of travel in zones, velocity in zones, the number of crewman on a shipment, the average distance from radiation source to crew, the number of handlings per shipment, the stop time per full-length trip, the minimum stop time per trip, the number of persons exposed while shipment is stopped, the average exposure distance for persons near the shipment while it is stopped, and so on.

Neutron Dose

Nevertheless, the RADTRAN III model is still deficient in several respects. RADTRAN III does not include a neutron dose. This is important for train crew, handlers and all persons within 150 meters of the shipping cask. Though curium-244 primarily decays with the release of alpha particles, spontaneous fissions account for 0.00013% of decays. Within this distance, for truck casks (NLI-1/2), gamma radiation is expected to provide 65% of the whole body dose, compared to 35% due to neutrons. For rail casks IF-300), the percentage of the whole body dose due to neutrons is 50% (Park85). These percentages hold for incident-free conditions, where the wet neutron shield remains intact. The relative neutron contribution is expected to be higher for the new larger capacity rail casks being considered by the Department of Energy.

Since the stainless steel outer liner of the neutron shield is only ¼ inch (Fischer87), it could be easily punctured in an accident . If the neutron shield tank is punctured, the neutron dose at the cask surface would increase by a factor of 35 (Park85). See Table 1. In that case, in an accident, whole body exposures to emergency personnel and crews due to a neutron dose will increase greatly over the dose estimated in RADTRAN III, even if there is no loss of containment.

Gamma Dose - Ground Reflection

In addition to this neutron dose, RADTRAN III does not include the entire dose due to gamma radiation. RADTRAN III includes only the direct gamma exposures. But an additional dose arises from reflection of gamma rays (Compton scattering) from the sky (skyscatter), and from the ground (groundscatter), the latter being more significant because of a three order of magnitude change in density (Sandquist85). Groundscatter can contribute up to an additional 25% to the gamma dose (Sandquist85).

Point Source vs. Line Source

Finally, RADTRAN III assumes the cask is a point source of radiation rather than a line source. For distances far from the cask, this is not significant, but for rail and truck crews, this is an important consideration. The effective radiation dose to crews and persons sharing the transportation link is increased if the radioactivity is assumed to be distributed along the cask's axis rather than at a point. Department of Transportation regulations require the dose to be less than 10 mr/h at any point 2 meters from vertical planes represented by the outer lateral surface of the transport vehicle.

The dose rate formula DR(r) employed by RADTRAN III is a function of the distance r from the center of the cask.

Dose rate formula $DR(r) = C \exp(-\mu r) * B(\mu r)/r^2$

where μ is the linear attenuation coefficient and B is the buildup factor which accounts for additional X-rays and photons produced when an energetic gamma ray loses energy. To more closely model reality, this formula must be modified in two ways. The dose should be a function of both r and z, the distance along the cask axis. Secondly, the build-up factor B, and the variable μr do not apply to neutrons. A completely different expression would need to be developed for neutron exposure.

ACCIDENT SEVERITY/RELEASE FRACTIONS

Fractional Occurrences

The amount of radioactivity which can be potentially released from a cask or the release fraction is a function of the accident severity, among numerous additional considerations. In RADTRAN III, the accident severity categories range from I to VIII, though this type of classification has now changed in the Modal Study (Fischer87), and is expected to change in RADTRAN IV.

In order to estimate the amount of radioactivity that could be released in a specific accident, we would also need to know:

(i) the likely response of the cask. For a specific accident, would the cask be breached? Would the valves open or the seals be damaged? Has the cask been constructed according to design and properly maintained?

(ii) the likely response of the fuel. Would the cladding and fuel pellets crack? How much radioactivity in the fuel pellets and gap would be available to mix with the coolant?

(iii) the transport and deposition of radioactivity within the cask. What is the interaction between the fuel pellets and the water, air or inert gas within the cask? What are the chemical and physical forms of radionuclides within the cask? What fraction of radionuclides would be released and what fraction would plate out in the interior of the cask?

In RADTRAN, however, accident severity categories are independent of the specific characteristics of each cask, though a generic highway and rail cask was considered by the Modal Study. New cask designs could alter this analysis.

In the six year period between NUREG-170 and RADTRAN II used in the Environmental Assessments, the fraction of accidents assigned by RADTRAN authors to the more severe categories, V through VIII, declined by a factor 690. This change took place with no change in the safety of shipping casks and with no new supporting data. Category VII and VIII accidents involve a breach in the cask wall greater than 1 square inch. Fractional occurrences, that is, the fraction of the overall truck accident rate in each severity category, are compared in Table 2 for NUREG-170 (NRC77), RADTRAN II User Guide (Madsen83), and RADTRAN II employed in the Environmental Assessments, which also holds for RADTRAN III.

We also note that RADTRAN II used in the Environmental Assessments places 99% of the accidents in categories I and II, with no accidents assumed in categories VII and VIII. The basis for the exclusion of categories VII and VIII in the Environmental Assessments is a consensus of experts at a workshop conducted by Sandia Labs (Wilmot81). Obviously, the "consensus" was only of those persons present, and not of the entire community of transportation experts. The workshop participants consisted almost entirely of industry representatives hand-picked by the Department of Energy, few state representatives and no members of public interest organizations or the National Transportation Safety Board. As recognized by Wilmot81, a "credible" accident scenario" is subject to a wide variety of interpretations, depending on the experience or point of view of each individual using the word." Contrary to the findings of the workshop, accidents involving puncture might cause accidents in severity categories VII and VIII (see section, "Puncture Analysis," and (Audin89)).

In Table 3, fractional occurrences are compared for train accidents. Note that the Environmental Assessments assume that 99% of all train accidents are relatively minor, categories I and II, and that no accidents leading to radiation release occur in the more severe categories VII and VIII.

High Consequence Events Eliminated

The Sandia Labs panel eliminated high consequence events, categories VII and VIII, by taking into account the low probabilities. "Unjustifiably conservative scenarios can be postulated, but they have no practical meaning because of their low probabilities." (Wilmot81) Thus, category VII and VIII events, which involve a breach in the cask wall greater than 1 square inch, were removed from the risk analysis, and only category VI and less, which involve a fine crack, less than 1 square inch, were retained. This methodology of simply eliminating low probability events is incorrect and based on a misunderstanding of probabilistic risk assessment.

In a probabilistic risk assessment, the risk is obtained by summing over the <u>product</u> of probabilities and consequences for all events which are physically possible. To eliminate an event, one needs to critically examine the risk of the low probability, high consequence events to see whether it is in same risk envelope as high probability, low consequence events. Only if the <u>product</u> of consequence and probability is low, can the specific event be eliminated. To eliminate an event, one needs to critically examine the risk of the low probability, high consequence events to see whether it is in same risk envelope as high probability, low consequence events. Only if the <u>product</u> of consequence and probability is low, can the specific event be eliminated. The workshop participants simply removed the low probability events from consideration without examining the product.

Another important reason for considering low probability, high consequence events is to identify the key elements in an emergency response plan.

Failure of Closure Seals/Welds/Fuel Assemblies

Major damage to the outer cask may be sufficient to vent the cask cavity through valve piping leading to the cask cavity. "The (Sandia) workshop participants decided that the most credible failure pathways for a cask are through a valve penetration and through a closure seal. Either failure could result in a pathway from the cask cavity to the environment (Wilmot81)." A 27-49 m.p.h. impact with a train sill was sufficient to produce a 2% strain in the outer cask structure (Fischer87). The Modal Study assumed, incorrectly, in our view, that higher loads on the inner cask shell were more likely to create a hazard. In fact, failure of the outer shell could sever penetrations to the inner cavity. This is an issue which remains to be resolved.

Cask closure seals can be damaged by either impact or heat. "A closure seal could fail if head bolts yield sufficiently to create a release pathway. The head bolts could be deformed mechanically or possibly by differential thermal expansion resulting from uneven heating of the cask head and body (Wilmot81)." Differential thermal contraction could also be caused by uneven cooling after a fire.

Contrary to the results of the Sandia workshop, the Modal Study (Fischer87) took strain as the key parameter in determining failure mechanisms.

In Table 4 we compare estimates of failure thresholds for release from spent fuel to cavity developed by the Sandia workshop and Modal Study. As seen in Table 4, the Sandia workshop took a 71g deceleration or 28 mph cask velocity impact as needed to rupture fuel assemblies, while the Modal Study assumed a 100g deceleration would rupture 100% of the fuel assemblies. For end impact, a 38g force or 41 mph crash was assumed to bend fuel assemblies.

In Table 5 we compare breaching thresholds for allowing release from a cask cavity to the environment. According to the Sandia workshop, a closure seal failure would occur with a side impact at 40 mph cask velocity, compared to the Modal Study assumption of 60 mph. For an end impact, a 48 mph cask velocity is comparable to the Modal Study (Fischer87).

Human Error and Sabotage

Besides the possibility of business as usual accidents, others may also occur because of human errors (e.g. incorrectly torquing head bolts or welding failures), and especially because of the sensitive nature of the cargo, sabotage. Probabilities, fractional releases and consequences can be greatly enhanced by human error and sabotage. Problems such as quality control, mishandling and organizational failures during loading and shipping are simply not factored into the RADTRAN III model and the Environmental Assessment (Audin87). As Freudenburg has pointed out, the Three Mile Island and Chernobyl accidents were greatly enhanced by the complicated interaction between humans and machines (Freudenburg88). Human interactions with complex machines are difficult to quantify, but this is critical in assessing consequences and probability (Freudenburg88). E.g., a crack in a cask can lead to lead voiding in fire. Human error can account for welding flaws.

Performing a task numerous times without incident can lead to declining levels of vigilance and increase the probability of an accident, such as occurred in the Valdez tanker accident. Over 8,000 tanker shipments had taken place in the port before the accident. Under the circumstances, it was difficult to retain attentiveness; the level of vigilance declined over time (Freudenburg89). Similarly, extremely severe nuclear transportation accidents are expected to occur rarely, but this expectation may lead to an increasing probability. As another example, while seeking certification from the NRC, the Department of Energy transported spent fuel from Brookhaven through New York City in uncertified containers(GAO88a). The Department, frustrated by their inability to obtain certification, became convinced the casks were safe enough and the Commission regulations were too much paperwork. Following the Brookhaven shipping campaign, the casks were withdrawn from service.

Puncture Analysis

Puncture analysis in the Modal Study does not appear to take into account realistic shapes of the impacting objects, e.g., if an object is sharp or pointed. In the Modal Study analysis, the train sill or striking object appears to be rounded*. The assumptions are not clearly stated and should be clarified. According to the Modal Study, a force must produce a pressure greater than 100,000 lb/ft^2 to have a strain on the inner shell greater than 0.2%. But the relationship between impacting

* The viewgraphs by M.C. Witt at the briefing before the Western Interstate Energy Board show a rounded edge to the impacting sill.

force and pressure depends critically on the shape of impacting object and the sophistication and realism of the computer model. If the object is pointed or sharp-edged, for a given force the pressure exerted may be greater, and the cask shell may be more easily punctured.

Qualitative vs. Quantitative

This raises another issue, the quantifiable vs. the difficult to quantify accident scenarios. A probabilistic risk assessment must sum over all accident scenarios, else the absolute risk is underestimated.

The issue of cask aging and its relation to failure in an accident is difficult to quantify. RADTRAN III and the Modal Study assume a "fresh cask." But welding failures, for example, may only become apparent after repeated use. The stresses a cask endures in loading and handling, and the vibrations in transit may contribute to the fatigue of cask components and welds.

Quantifying the pressure exerted by a punch is an extremely complex problem. For a right cylindrical punch, experiments show that only the perimeter of a punch contacts the plate (Larder80). Therefore, the contact pressures are much higher and localized than might be expected. In addition, large biaxial tensile membrane stresses develop in the test plate near the punch. Off center puncture forces appear to stretch and tear the stainless steel plate (Larder80). These dynamic forces, for real physical objects such as the train sill of an engine, are difficult to quantify, but are crucial in determining whether the steel shell is actually pierced. Puncture analysis depends critically on the shape of the punch and where the puncture forces take place (Larder80).

Though the NRC contractors for the Modal Study did employ a more sophisticated computer analysis using NIKE IID for several computer runs, the actual puncture objects may not have been realistically modelled. Rather, the NRC contractors took into account the low probability of puncture events and assumed impact forces could generate higher loads (Fischer87). In sum, the Modal Study simply chose to ignore puncture events.

Though the Department's EA states that is important to have confidence that the analytical results closely represent reality, and that "the correlations have been reasonably close," we do not share this confidence for puncture analysis. It is important to emphasize that the accident severity categories of RADTRAN III and the Modal Study are strictly a function of impact and fire; puncture is simply excluded as a variable.

Accident Probability

Whatever estimate of accident probability is arrived at needs to be supplemented by confidence levels. Unfortunately, accident data, particularly for rails, are notoriously unreliable. The General Accounting Office found deficiencies in the Federal Railway Administration's rail accident data, especially under-reporting (GAO89). Data reliability is also a key issue for the Modal Study.

It is often not clear when RADTRAN III is relying on data or expert judgment. If expert judgment is used to estimate this probability, Delphi-type techniques can be used to reach some consensus, providing all expert judgment is included. Of course, predictions by experts are routinely off. The difference between the consensus figure and the initial estimates would give some indication of the confidence level. Preferably systematic errors could be addressed by requesting subjective confidence ranges from each panelist and weighting these ranges according to the assumed expertise of each panelist or his/her subjective confidence.

HEALTH EFFECTS MODEL

External exposures are calculated by direct exposures to localized source, exposures to contaminated surfaces (groundshine), and penetrating radiation from a passing cloud (cloudshine). As mentioned above, the model omits a dose due to gamma reflection from ground and air and a dose due to neutron exposure.

RADTRAN II did not include health effects due to ingestion of contaminated food and water. The Department of Energy assumed interdiction and food confiscation. "The local authorities are assumed to intervene by impounding crops and cleaning up contaminated soil (Madsen83)." Under RADTRAN III, a crude food ingestion model can be utilized. Cloudshine can be factored into RADTRAN by adjustment of inhalation toxicity parameters.

Cancers and Radiation Dose

The health effects model and input parameters in RADTRAN III have not changed from the Rasmussen study (NRC75), though recent data suggest that a change in input parameters is warranted. Radiation doses in the model are due to gamma exposures and to ingestion and inhalation of radionuclides.

Given a direct exposure, RADTRAN assumes one latent cancer fatality for 10^4 person-rems whole body dose to the population. This latent cancer fatality rate is based on a 1965 study of Japanese bomb survivors by Oak Ridge National Laboratory (ABCC68), and is probably not conservative. More recent data by (Preston87) and others suggest that the rate is closer to 16 latent cancer fatalities per 10^4 person-rems. This latest data is greater than assumed in RADTRAN III, but less than the results of (Mancuso83), 38 latent cancer fatalities per 10^4 person-rems. The Mancuso study was of government workers at the Hanford facility, exposed, on average, to twice background radiation levels. The recent UNCEAR report (UN88) estimates eight latent cancer fatalities per 10^4 person-rems. Thus, RADTRAN III is now at the low end of the spectrum. These estimates may change further with evaluation of Department of Energy nuclear worker data being turned over to the TMI Public Health Fund.

Lung Model

In a severe transportation accident, radionuclides may be dispersed into the air and be inhaled by people downwind. The lung inhalation dose is a major cause of latent cancer fatalities in a transportation accident. Depending on the physical size of inhaled radionuclides, they can be deposited in the nose (nasopharyngeal region), bronchial tract (tracheobronchial region) or lung (pulmonary region) (NRC75). From these initial locations, radionuclides may be absorbed by blood or lymph nodes, or move to the gastrointestinal tract, where they may be eliminated or be absorbed into the blood stream. In these six compartments, radionuclides can decay, leading to a radiation dose to the lung, blood, lymph nodes or GI tract. The lung model employed is an adaption of the ICRP lung model (ICRP62). Tables have been developed by Kocher et al to estimate these radiation doses (Kocher87).

Several issues must be resolved here. 1) Is the chemical form and physical size of radionuclides released in a spent fuel transportation accident the same as those from a reactor accident? This affects where inhaled radionuclides are deposited in the body and the lung clearance times. A transportation accident could involve oxidized fuel of one micron size particles which deposit most effectively in the lung. 2) Does the closer proximity of persons to the accident, compared to a reactor accident, affect the type and size of radionuclides inhaled? 3) Is the accident scene correctly modeled? The amount of radioactivity inhaled depends critically on a realistic accident scenario. At an accident, traffic may become congested as the curious gather until the crowd is dispersed by local emergency personnel who recognize the radiation hazard. The size crowd and their proximity to the accident depend on the location of the accident, time of day, availability of access routes and so on. Inhalation exposures also depend on the nature of the accident, whether fire is involved, meteorological conditions (wind, turbulence, precipitation) and physical setting (open space, confined corridors, reservoirs). All these real-life factors are important in predicting lung inhalation exposures. Instead, for lung dose calculations, RADTRAN III assumes an exposure time of 15 minutes for early health effects; for delayed effects, RADTRAN III assumes a residence time of one hour in urban regions, and two hours in suburban and rural regions.

Realistic Accident Scenarios

While RADTRAN III can calculate the radiation exposures to a given population given the population density and air concentrations, the actual exposures in a real-life accident could vary by orders of magnitude from those predicted. RADTRAN III assumes that persons are exposed for one day and evacuated for ten days during which time the area is surveyed and decontaminated or interdicted. These unrealistic assumptions obviously limit the radiation exposures received. Radiation exposures in a city are a function of the variables mentioned in the preceding paragraph and also the evacuation procedures. Contamination of interior spaces and resultant exposures also depend on the season (air conditioners) and the ventilation of buildings (windows or central air intake).

ECONOMIC PARAMETERS AND MODELING ASSUMPTIONS

To evaluate the reasonableness of technical and socioeconomic assumptions and to provide insight into the cleanup process envisioned by RADTRAN III and to review the changes from RADTRAN II, we evaluated one example in detail, the dispersal of radioactive materials from a severe spent fuel accident in an <u>average</u> rural area. Transportation accidents causing radiation contamination in urban areas have been considered in great detail by the Nuclear Regulatory Commission (NRC80), but rural areas have not been greatly studied. We used the PATHRAE-T computer code (Sandquist85) to determine the ground concentrations, and then considered detailed decontamination of the rural area under 3 options of RADTRAN III. We then compared these 3 cleanup options with a fourth option, scraping a large land area. Though we disagree that severe accidents, severity categories VII and VIII should be excluded, for the purposes of this discussion we assumed the fractional releases postulated in the Yucca Mountain Environmental Assessment. Though larger capacity casks will be employed in the future, we assumed, following the Department's Environmental Assessment, that a rail cask containing 14 PWR fuel assemblies, 5 years out of the reactor, is involved in an impact accident in which the fuel rods burst and uranium fuel is oxidized, leading to a release of 1380 Ci. For the purposes of this discussion, only the gamma dose due to deposited radionuclides is considered.

An impact, burst, oxidation accident is a severity category VI accident. In such an accident, the fuel cladding is assumed to partially fail under impact. External heating is also assumed to produce internal pressures in the fuel sufficient to burst the cladding. Rapid oxidation, from uranium dioxide to U_3O_8 cracks the fuel and enhances the release of radionuclides.

It is important to recognize that the Environmental Assessment does not contain costs to decontaminate an area following a radiation-related accident. Similar to health effects estimates which are the output from RADTRAN III, the economic costs to decontaminate a region following an accident are automatically output from RADTRAN III. We believe it required a conscious decision by the Department of Energy to exclude these costs from the Environmental Assessment.

The radioactive material that is released to the environment is dispersed downwind, using a modified Gaussian dispersion formula which accounts for depletion of the plume as radioactive particulates settle out. Doses to downwind residents are due to inhalation, direct radiation from the passing cloud (cloudshine), ingestion of food and water, and gamma radiation due to radionuclides which are deposited on the ground (groundshine). To calculate the extent of ground contamination, we employed the PATHRAE-T computer model (Sandquist85).

Decontamination and the economic parameters in RADTRAN III are based on the following assumptions: contaminated areas will be cleaned up to some level if possible and areas which have reached that level are considered fully useable, though potential health effects will continue to occur. The ratio of initial contamination level and acceptable residual level is called the decontamination factor, DF.

RADTRAN Cleanup Assumptions

RADTRAN III makes the following assumptions:

1. People are exposed for the first full day following the accident. Surveys are conducted and a determination made for need for evacuation, decontamination, interdiction, etc. This assumes a fairly quick and effective evacuation.

2. If DF is ≤ 1.0, no remedial action is required; and persons are exposed for 50 years to radiation from initial deposition, reduced by radioactive decay.

3. If DF is ≥ 1.0, a 10-day survey/cleanup period is assumed during which no population exposure is accrued. In certain rural areas, containing dairy farms, for example, this assumption would have major economic implications which are not incorporated into the RADTRAN III model.

DF = 0.1 is assumed to be the minimum level of detectability. DF = DF2 is the regulatory cleanup level (in $\mu Ci/m^2$) that must be specified. We take the acceptable decontamination level to be 0.2 $\mu Ci/m^2$, the clean-up criterion for the Palomares, Spain accident. This corresponds to a groundshine dose of DF2 = 15 mr/y, employing the expression for dose assumed by RADTRAN III:

$$DR = Q_7 * CLVL * E_d \quad \text{(Rem/day)}$$

where CLVL = contamination level ($\mu Ci/m^2$)

E_d = total photon energy/dis (MeV)

$Q_7 = 3.04 * 10^{-4}$ rem-m^2/day-Ci-MeV

DF3 = 20.0 is the maximum contamination level in the low to moderate contamination range and corresponds to a yearly dose of 300 mr/year. DF4 = 40.0 is the maximum level for which cleanup to the criterion level is feasible, and corresponds to a yearly whole body dose due to ground gamma radiation of 600 mr/y.

If DF is ≥ DF4, three options are considered in RADTRAN III. Under option 1, areas with 1 < DF < 40 are cleaned up and areas with DF ≥ 40 are interdicted. Under option 2, areas with 1 < DF < 40 are cleaned up and areas with DF ≥ 40 are razed and rebuilt. Under option 3, no cleanup is performed and all residents are evacuated until the hazard is gone.

The economic impact cost expressions are given in Table 7.

Under RADTRAN III, Option 1, all areas between 15 and 600 mr/y would be cleaned up; areas with dose greater than 600 mr/y would be interdicted. Under Option 2, the same area would be cleaned up, but the area with dose greater than 600 mr/y would be razed and rebuilt. Under both options, if the area with DF ≥ 40 is less than 500 m^2, the area is added to the region with 20 < DF <40. Under Option 3, the entire area would be interdicted until the hazard was gone due to radioactive decay. Under this option, the area would be progressively resettled, as the radiation levels in each region decay to the criterion level, 15 mr/y. In cases where there is some uncertainty, each option is considered and the lowest cost option is assumed in RADTRAN III.

Under an impact, burst and oxidation (category VI) accident, the contaminated areas are given in Table 8. As is seen, the area with contamination > 0.2 $\mu Ci/m^2$ is 110 km^2. Category VII and VIII accidents would give rise to a much larger contaminated region.

Economic Costs for Rural Cleanup

The costs for decontamination of a rural area are presented in Table 9. As seen in the Table, the area with a gamma dose between 1.5 and 15 mr/y (990 km^2) is surveyed and released. Assuming half the land is tilled, crops are purchased and the land resettled. The cost, primarily for surveying this large area, is $116 million.

Under Options 1 and 2, the area with radiation dose between 15 and 300 mr/y is surveyed, deep plowed and resurveyed, crops are purchased and dwellings cleaned. Under Options 1 and 2, this cleanup of 104.6 km^2 is assumed to take only 10 days, during which persons are evacuated, income lost and the area guarded. It is difficult to understand how a large survey force could be mobilized to carry out its function within ten days. Nevertheless, the total cost to cleanup this region is $35.75 million. Not included in this cost are losses to farm income if cows and other animals are left untended. In the region where the ground gamma dose is between 300 and 600 mr/y (2.8 km^2), land is either scraped and buried, with crops purchased, or deep-plowed twice. Again, evacuation, security and personal income loss is for 10 days, and a more extensive dwelling cleanup is undertaken. The cost for cleaning this region is $1.36 million.

For the most contaminated region, where the ground gamma dose is > 600 mr/y, the area is interdicted under Option 1. All persons are evacuated and given permanent relocation expenses, land is purchased and guards are posted for approximately 160 years while ground gamma levels decay to 15 mr/y. The cost for interdiction of this heavily contaminated area is $22.3 million, primarily for security. The total decontamination cost under Option 1 is $175.75 million.

Under Option 2, rather than interdiction, the most heavily contaminated region is extensively cleaned. Land is scraped and buildings are razed and reconstructed. The total time for this work is 470 days, during which persons are relocated and personal income lost. The cost for extensive cleanup of this region is $79.74 million and the total decontamination cost under Option 2 is $233.18 million.

Under Option 3, no cleanup is performed and all residents are evacuated. Resettlement occurs as contamination levels are reduced to 15 mr/y. As was clear in the case of Love Canal, public acceptability and assurance are key factors in whether an area is resettled. The major cost under this option is security to guard a vast area for up to 160 years. The total cost for Option 3, as shown in Table 8, is approximately $553.85 million. Since the RADTRAN III model does not discount future dollars, this figure is probably high.

To summarize, the total decontamination costs under RADTRAN III for a transportation accident in a rural area, including replacing lost wages, lost crops, evacuation and security, under options 1,2 and 3 are $176 million, $233 million, and $559 million, respectively. The times for cleanup or remediation for these three options were ten days, 470 days and 160 years, respectively. RADTRAN III automatically selects the least expensive option, option 1, costing $176 million and requiring a ten-day cleanup period.

Alternative Cleanup Model

As an independent check of the decontamination costs projected by RADTRAN III, we use the computer model PATHRAE-T (Sandquist85) to calculate surface contamination levels. In the Environmental Assessment, the Department of Energy employed PATHRAE-T to estimate the health effects due to an accident, but ignored the economic costs.

Assume that the region with DF ≥ 1, where whole body doses are ≥ 15 mr/y, is scraped to a depth of 10 cm and the contaminated earth is transported and buried. A range of clean-up costs can be postulated, depending on how the contaminated earth is packaged and "disposed of." Assuming the costs are the same as for the Vitro tailings pile in Salt Lake City, the cost for loading is $\$10/m^3$, the cost for transportation $\$15/m^3$, and the cost for disposal $\$5/m^3$. On the other hand, if we assume the scraped earth is treated as "low-level" waste and is disposed of at the Barnwell facility, the cost for packaging is $\$430/m^3$, transportation $\$530/m^3$, and disposal is $\$510/m^3$.

To scrape and bury an area where DF ≥ 1 to a depth of 10 cm, implies 11 million m^3 of contaminated earth, at a waste management cost ranging from \$330 million to \$16.2 billion, the latter figure if the contaminated earth is classed as "low-level" waste. Judging from the enormous quantity of contaminated earth, it is more likely that it would either be handled as tailings or the land would be interdicted. A combination of these two approaches was used at Chernobyl. In addition, according to RADTRAN III, assuming ½ the rural area is tilled, crops would be purchased (\$1.93 million), two radiation surveys would be conducted (\$22 million), and evacuation and personal income loss would amount to \$10.3 million. A major cost is razing and constructing buildings in a rural area. For a region as large as 110 km^2, this cost is \$3.19 billion; this cost is only \$76.3 million if the region is limited to 2.63 km^2, with radiation levels ≥ 600 mr/y. Thus, the total costs in this fourth option would range from \$464 million to \$19.4 billion.

Costs in the billion dollar range also result from scaling up costs in the Palmomares, Spain cleanup. In that mid 1960's accident, the chemical explosives in two nuclear warheads detonated, distributing plutonium over a 2 km^2 area. The cost and time to clean up this contamination was approximately \$60 million and three months, respectively. Scaling these numbers up by a factor of 50 to represent the area impacted by a transportation accident, the cost and time to clean up a rural accident could be \$6 billion (in 1989 dollars) and 12.5

years. Obviously this analysis cries out for a more detailed engineering estimate, but it lends support to cleanup costs in the billions of dollars, as estimated above. In contrast, the costs under Option 1 of RADTRAN III are $176 million. Costs could obviously vary by orders of magnitude depending on geographic location, property type and decontamination techniques used.

Many of these cleanup costs exceed coverage for the Department of Energy under the Price-Anderson Act, $500 million. Since the Department takes title to spent fuel in 1998, the shipment falls under the $500 million Price-Anderson Act limit. Our analysis of insurance underwriting practices below leads us to conclude that, barring federal backing, private insurers are unlikely to insure high-level waste shipments.

Critique of RADTRAN Economic Assumptions

Comparing the cleanup costs of RADTRAN III and PATHRAE-T, the greatest uncertainty and weakness in RADTRAN III appears to be in the sociological and political assumptions and the economic parameters. The RADTRAN III model displays its roots - developed by physical scientists and engineers in a laboratory removed from the representative population. RADTRAN III only assumes the purchase of crops, not animals or milk, or even high density crops, such as grapes. Costs can vary substantially depending on geographic location, property type and decontamination techniques used. Clearly, agricultural costs in much of Nevada would be much less than in a grape-growing district of New York or dairy farm regions of Wisconsin. An accident occurring near Texas stockyards could be very costly. It is not unreasonable to expect that the cleanup costs could vary by a factor of 10 or more depending on the agricultural region. This argues for conducting a route-specific rather than generic analysis. We recommend that a rural economist review the cost of purchasing crops, razing buildings, and so on.

Judging from the events in Palomares, Spain and Goaia, Brazil, it is likely citizens will exert political influence to have an area completely decontaminated, to have dwellings, buildings and land extensively cleaned and certified to be at background levels - that is, citizens and communities will want "to be made whole" following an accident. It will be difficult to persuade some citizens to accept having cesium deep plowed while others have land scraped and made fertile. The more likely scenario is either complete cleanup or interdiction. This means that the entire area with dose levels greater than 15 mr/y will be scraped and buildings within that area will be extensively decontaminated, with the land brought up to its previous fertility. The other likely alternative ala Love Canal is that a major area would be interdicted and residents relocated to new jobs and new homes. If residents must be relocated out-of-state, then the state could request payments to replace lost taxes. RADTRAN III does not account for the fact that the entire community infrastructure would be dismantled in a major accident. Public acceptability is a key unknown. Resettlement of an area may not be a socially acceptable option.

For economic calculations, costs associated with litigation, government actions, indirect corporate losses and land devaluation are ignored. RADTRAN III does not properly take into account the indirect costs of a major contamination accident, just the direct costs such as crop purchases, and business and personal income loss. In a rural area, other businesses, not necessarily within the contaminated region, depend on farmers, such as seed companies, equipment suppliers, lumber and other suppliers, groceries and other retail businesses, such as clothiers. These indirect costs may more than double the direct losses (Bischak89). This is a major oversight of RADTRAN III which understates accident cleanup costs.

The cleanup time projected by RADTRAN III, which has not changed from earlier RADTRAN versions, is highly unrealistic. RADTRAN III estimates 10 days to conduct radiation surveys of 110 km^2, including buildings. Without proper planning, it is unlikely a cleanup crew could be mobilized in that period of time, let alone perform the survey. According to Sandquist85, the estimated cleanup time to scrape and dispose of 11 million m^3 is 460 days. The basis for this number is not explained in Sandquist85 and conflicts with the actual cleanup of the Palomares, Spain accident, which required three months to cleanup 2 km^2 (NRC75).

In contrast to rural cleanup costs, the economic parameters for an urban clean-up are greatly revised upwards in RADTRAN III (Madsen86). For example, the cost to raze and rebuild an urban area is now estimated to be \$3.6 billion/km^2. Assuming an impact, burst and oxidation accident, the cost only to raze and rebuild a heavily contaminated urban area (2.63 km^2) is \$9.5 billion. The land value, assuming 10,000 persons/km^2, is now estimated to be \$6 billion, which is a considerable underestimate for Manhattan and perhaps for Las Vegas, but probably adequate for other large cities. The time required to cleanup an urban area under RADTRAN III is 540 * A_4, or almost four years. These estimated costs and cleanup times are probably low for New York City and other major densely populated cities, but probably high for most U.S cities. Under these assumptions, the personal and corporate income loss, and the loss to state and local taxes, would be enormous. The economic losses in an urban area are greatly increased in RADTRAN III, but Price-Anderson insurance would pay back less than 10¢ on the dollar. These dollar costs predicted by RADTRAN do not include medical and other costs associated with an increase in cancers or genetic effects.

We recommend here that a real accident scenario for an urban area such as Las Vegas be constructed. The actual road and rail locations should be considered relative to business locations, population densities, and so on. The effect on Las Vegas and the state of Nevada of an extended time for evacuation and interdiction should be incorporated into economic cost and health effect estimates.

NUCLEAR TRANSPORTATION ACCIDENTS AND INSURANCE COVERAGE*

The RADTRAN model, in particular, but also any other PRA model, is suited to assessing insurance requirements. The RADTRAN model estimates the number of health effects per year and the dollar cost per year due to transportation accidents or normal transport. The number of health effects per year or the dollar cost per year is the expected

* This section written with the assistance of Dr. Maarten DeKadt, based on letters to M. Resnikoff, dated April 2, 1989 and July 16, 1989.

value. In many years, accidents will be minor and not give rise to radiation-related health effects, but with a small likelihood, an accident in any year could be severe and lead to a major radionuclide release. The clean-up costs in a metropolitan area could rise to $10 billion, as shown above. In some sense, the RADTRAN model is like estimating the number of deaths per year due to an unlikely event like a dam break or airplane crashing into a sports stadium and converting this number into fatalities per year.

In this section, we discuss in general terms how RADTRAN can be adapted to determine insurance coverage for carriers, though we have not had sufficient time to develop the details. Assuming the State had this power, Nevada would need to specify just one number, a not-to-be-exceeded likelihood that costs exceed the insurance coverage level.

Determining Carrier Insurance

To determine insurance coverage requirements, each accident-related event must be characterized by its probability of occurrence and the fraction of high-level waste released. Since casks are not tested to destruction, the uncertainties in correlating accident severity and release fraction can be large. Nevertheless, using RADTRAN the potential dollar consequences of each accident event can be estimated. Thus, the probability of an accident and the magnitude of costs attached to that event can be estimated. Given the routes, transportation modes and number of shipments per year per mode, a cost curve can then be developed by summing estimates of probability and magnitude of costs for each event. This can be plotted as a cost curve, shown in Figure 1. The y-axis denotes the likelihood of exceeding a specified cost in an accident; the x-axis is the cost of a single accident. We have not had sufficient time to plot the actual cost curve using RADTRAN and Nevada accident statistics.

The cost curve illustrates graphically for each possible cost in an accident, the likelihood the cost would be exceeded. As seen, for minor accidents with low dollar costs, the likelihood is high the cost would be exceeded, and for very high accident costs, the likelihood is low the costs would be exceeded. Step-wise drops are also shown on the cost curve, corresponding to discrete changes in accident severity levels. At these changes in accident severity levels, the Department of Energy assumes a non-continuous change in the amount of radioactivity released.

If the State specified a not-to-be-exceeded likelihood, i.e., a point on the Y-axis, the dollar cost on the X-axis of Fig. 1 would specify the coverage levels. With the cost curve in Fig. 1, the State could establish that with an estimated probability, a high-level waste truck would cause accident-related costs of X dollars or more. Assuming the State had such authority, it could then require insurance coverage of X dollars per truck per year. A different acceptable level of the likelihood of exceedance would imply a different coverage level (Karam88).

This type of analysis could make sense to an insurance company only if the uncertainties in the cost curve were small, and if the potential accident costs were not excessive. Neither is the case with high-level waste transportation and insurance companies would require therefore that a cap be placed on the aggregate coverage, which is precisely what is done under the Price-Anderson Act. The Price-Anderson cap is $500 million for Department of Energy shipments. Without this cap, insurance companies face the possibility of going bankrupt in one accident.

Insurance Practicalities

To narrow the uncertainties, automobile insurance companies attempt to identify all risks. Specific information required by insurance companies include: occupation or business of applicant, number of years in the business, policy period, type of coverage desired, limits of liability required, and specific information about the use of vehicles. A complete list of owned vehicles is required as well as information on the drivers and the experience over the past three years.

To expand on these points,

- the type of business is an indication of the nature of the hazard.
- the number of years in the business is an indication of the experience of the operators of the business. Particularly

desirable risks were those who were in business for some time with few accidents and therefore low claims payments.

- the policy period defines the period of time the insurance company has a financial obligation. This issue has become critical in the lack of insurance for hazardous waste disposal companies (GAO88b), where the liability extends far into the future.
- the limits of liability define the level of financial obligation.
- questions are specifically asked about the transport of explosives, which might lead to rejection of the risk since transporters can assume a specific number of accidents per mile. With hazardous or radioactive wastes, any and every accident can attain an insurer's limits of liability.
- driver experience is used as a predictor of possible accidents. Drivers without accident records are preferred. The size and experience of the fleet is important.
- the complete list of vehicles is necessary not only for rating purposes, but to enable insurance company representatives to visit the potential insured's property and inspect the condition of vehicles. The care and maintenance of the automobile fleet is used as an indicator of the care and safety concerns of the drivers.

In addition to the above, insurers of radioactive waste shipments would consider the routes traveled, equipment used to contain and secure the waste, the trucks used to transport the wastes and the experience of the drivers.

If the insurance market were "free", rather than risk limited by a Price-Anderson cap, the premium would be related to the risk and insurance carriers would seek to limit this risk in various ways. For example, risks are sometimes retrospectively rated. Actual loss payments can be reimbursed by the shipper to the insurance carrier at the end of the policy period by a formula agreed upon when the insurance was issued. Or, at even less risk to the insurance carrier, "fronting" policies can be written. In this case, letters of credit from the insured to the insurer can be written for the entire amount of the limits of liability. Only financially able trucking firms can afford this type of "insurance."

In deciding whether to insure a shipper, statistical and underwriting analysis is fundamental, but judgment may be primary. In the case of nuclear waste transport, where experience data is not subject to actuarial science, the judgment of underwriters dominates. Underwriting analysis consists of four parts: underwriting guidelines (does the insurer want to cover nuclear shipments -- a judgment call), engineering surveys of similar facilities (trucks themselves and road accidents in general), inspections of these and other facilities (vehicle condition), and review of losses already experienced at the facility to be insured. On this last point, the General Accounting Office has pointed out (GAO88b) with regard to hazardous waste facilities, "Among the factors that affect risk are the quantity and type of waste handled by the facility, how close the facility is to water and to metropolitan areas or farms, and the facility's security procedures." Thus, the risk becomes worse if it is near a metropolitan area or near water.

"Underwriting judgment" is always used in the final weighing of the information available about any risk. According to the General Accounting Office (GAO88b), "Whatever combination of statistical and actuarial analysis or underwriting analysis is used, there still remains an element of professional judgment in determining insurance rates. In the case of pollution liability insurance, where any actuarial data base is extremely limited and where underwriting analysis always contains uncertainties, ratesetting -- and the decision to write this line of insurance at all -- must be based on professional judgment and must be sensitive to external factors more than most other lines of insurance."

The application of the above to nuclear shipments is the following:

- no large numbers to which the law of large numbers can be applied,
- no large pool of potential insured to which the concept of sharing of risk can be applied,
- no long-term experience to support actuarial methods,
- potential of losses large enough to subject any insurance policy to whatever limits of liability it may contain,

- lack of willingness by insurers to write potentially less hazardous risk (insurers in the State of New York are averse to writing policies for petroleum spills),
- leads to the conclusion that insurers would evaluate nuclear shipments as an exposure associated with risks that are too large for them to take on. No coverage would be available, outside of any government mandated pool or consortium.

SENSITIVITY ANALYSIS

The sensitivity analysis for incident-free transport in RADTRAN III provided expressions for calculating the "importance measure" (Eqs. 48-51, Madsen86). While the algebraic derivation was correct, the subsequent discussion that centered around Tables 6 and 7 is confused. The importance measure of one variable (x_i, say) will depend on the value of the other variables (x_j) because the function $d_i(x_1, x_2, \ldots)$ for variable i is usually not separable in the other variables. Thus, one cannot talk about the importance measure of one variable without also mentioning the magnitudes/levels at which all variables are. It is customary to estimate the sensitivity of each variable (characterized by the "importance" measure) at some base case. This also means that in the worst case many of these parameters could be different from that assumed for the base-case analysis. All of this should be clarified in RADTRAN III.

In contrast to RADTRAN II, there appears to have been some sensitivity analysis performed for vehicular accidents in RADTRAN III. It is mentioned that the problem "is far too complex to be amenable to a closed-form analytical treatment..." (Madsen86). Then, the RADTRAN III report provides some vague suggestions on how the problem can be rectified. There are a number of Monte-Carlo techniques for estimating sensitivity in cases where closed form solutions are not possible. Monte-Carlo simulations are used to derive distributions of the impact vis-a-vis some parameter. In cases where extremely large quantities of data are required to derive this distribution, a technique called "Latin hypercube sampling" is most frequently used.

Sensitivity information in the case of vehicular accidents is particularly needed for the impact of the following variables: accident rates for all transportation modes in urban, suburban and rural settings, accident severity levels, percent and type of radionuclides released, meteorological assumptions, dilution factors and all the delay assumptions.

STATE OF NEVADA COMMENTS ON DRAFT ENVIRONMENTAL ASSESSMENT*

Section A.8 Risk Analysis

1. *Regional Risk Analysis. Draft EA estimates risk in terms of person-rems, not latent cancer fatalities.*

This has been corrected in the final EA, but, as indicated in the Health Effects comments above, the latent cancer fatality rate is too low and does not reflect the latest data.

2. *Generic risk analysis relies on national or average accident data rather than route-specific data.*

This has been corrected in the final EA which shows that the number of rail accidents per mile are less in NV, but highway accidents per mile are much higher.

3. *Risk estimates for nationwide system are inadequate and fail to:*

■ weather conditions and weather-related stops

Though RADTRAN III now contains additional parameters that allow for stops, this matter has not been addressed in the final EA. Weather-related stops should also include over-heated trucks.

■ health effects due to ingestion of contaminated materials in the event of a serious accident involving radiation release.

RADTRAN III now has a crude food ingestion model. Specific radionuclides cannot easily be accommodated in RADTRAN. For example, the iodine dose to the thyroid is not included in the model.

* Comments by the State of Nevada appear in italics, followed by Associates comments.

■ *the effects of barge transportation and unit or special-train service.*

The Environmental Assessment now has an analysis for barge and unit trains, but not all factors, such as a 90 mph crash are included.

■ *% train vs. truck.*

This is not too important since DOE bounds results by using 100% truck or 100% rail.

■ *an analysis of least risk alternatives.*

DOE claims it is too early to do this analysis, which has not yet been done; a route-specific analysis, required to determine least risk, has not yet been conducted.

■ *radiation exposure during normal highway transport to vehicles in adjacent lines of traffic.*

This has now been done, using the PATHRAE-T computer model.

■ *effects of peak transportation accidents that reflect real world conditions.*

This has not yet been done, particularly a detailed analysis for Las Vegas.

4. *Probability of accidents. General accident probabilities for spent fuel accidents from 1971 to 1980 used; should use early than 1971 and later than 1980.*

This has not yet been done by DOE, but data of DOT Bureau Motor Vehicle Safety could be used, as in the Modal Study. This would increase accident probability by a factor of 4. Data reliability is an important issue. GAO found deficiencies in the Federal Railway Administration's rail accident data (GAO89).

5. *Probability of serious accidents. Since no accident data for serious accidents, the probability was estimated. Confidence limits should have been placed on such estimates. In addition, probability*

estimates should have included the potential for sabotage as well as routine highway accidents.

Confidence limits were still not placed, particularly for sabotage and human error. **This is an important issue** which should be addressed.

6. Sensitivity analyses. Neither the draft EA nor any of the reference documents cited in the draft EA include sensitivity analyses of risk models. Analyses should include variations in the following:

- *accident rates for rail and truck transport in urban, suburban and rural population zones.*

Yes, including a distribution of speeds.

- *changes in the accident severity assumptions.*

This should be done by Nevada, but has not yet been done by DOE.

- *changes in radioactive release assumptions.*

This should be done by Nevada, but has not yet been done by DOE.

- *changes in assumptions regarding the percent of radionuclides released, aerosolized and inhaled.*

Not only this, but a comprehensive list of specific radionuclides released. RADTRAN does not easily allow this, except to run RADTRAN several times with different radionuclides. The DOE included a short list of radionuclides.

- *changes in stop times.*

RADTRAN III has been corrected to allow these parameters, but the DOE has not carried out the sensitivity analysis.

- *changes in meteorological assumptions that determine the dispersion of radionuclides in the event of a release.*

Analysis should include wet v. dry deposition; maximum consequences should include truck or rail accident and downwind deposition of radionuclides in Las Vegas.

▪ *changes in assumptions related to the configuration of truck stops.*

This should be done by Nevada, but has not yet been done by DOE.

▪ *changes in assumptions related to population densities.* This should be done by Nevada, but has not yet been done by DOE (day-time vs night-time populations, distance of nearest individuals, etc.).

7. *Criteria for data inputs for risk models. DOE should clearly distinguish between inputs based on real data and those based on engineering judgments.*

This has not been done in the final EA, and is an important consideration.

A.9 Cost Analysis

1. *Total estimated costs reflect only shipping charges, hardware expenditures, and maintenance allowance. This fails to include:*

▪ *costs of emergency planning.*

This has still not been done in the final EA, though DOE says this will be done in EIS.

▪ *costs associated with evacuation and clean-up in the event of a serious accident.*

Though these costs were calculated by RADTRAN III and PATHRAE-T, they were not included in the final EA. DOE selectively used (Sandquist87) data (for vehicles moving in adjacent lanes, e.g.), but did not use their data for clean-up costs which were calculated by Sandquist87 for a rural accident ($620 million, 460 days to clean-up; costs would be much higher for an urban accident, as discussed above).

■ costs of constructing roads and rail lines needed for direct access.

This has still not been done for a rail line.

■ costs associated with upgrading road-beds and rail lines.

This has still not been done by DOE.

■ costs incurred by increased damage to highway road-beds.

This has still not been done by DOE.

■ costs associated with inspection and enforcement.

This has still not been done by DOE.

2. *Costs associated with shipping defense waste from all 3 DOE sites.*

This has now been done for equipment and maintenance costs, expanding analysis from SRP alone.

3. *Cost elements vary among EA's.*

This may now be moot, no?

4. *Sensitivity analyses have not been included for cost estimates.*

Except for 100% rail vs. 100% truck, this has not yet been done.

<u>A.10.4 Insurance Coverage for Transportation Accidents</u>

All coverage under Price-Anderson Act, according to DOE. Does this represent adequate coverage? Who would be liable for greater than $500 million?

As discussed above, the maximum credible urban and rural accidents would both greatly exceed $500 million.

Nearly every state supports the concept of strict and unlimited federal liability for any and all accidents. Does DOE support this concept?

No, perhaps only when taken to court.

CONCLUSIONS AND RECOMMENDATIONS

Clearly RADTRAN III has major defects which must be improved in the next version. These deficiencies are summarized in Table 10, and discussed below.

- The RADTRAN III model must be further improved to include dose from neutrons, gamma reflection and a line source.
- A major disagreement remains regarding the inclusion of radiation releases from severe accidents, categories VII and VIII. We recommend that the risk of category VII and VIII accidents be calculated to determine whether the effects would be small or large.
- Human error and sabotage must be factored into the RADTRAN III model.
- While RADTRAN III now includes a food ingestion model, the health effects model must be updated to include the latest data on Japanese bomb survivors. Without these factors, RADTRAN III understates the health impacts of transporting high-level waste to the proposed Yucca Mountains repository.
- Our calculation of the economic costs of cleanup of a rural area under RADTRAN III shows that the estimates can vary by a factor of 5 depending on the assumptions. The time for cleanup or interdiction could range from 10 days to 160 years. We regard the 10 day figure as unrealistically low. The social and political assumptions which underpin the RADTRAN III model must be carefully reconsidered.
- The economic costs calculated in RADTRAN III are direct losses, not indirect losses or costs of cancers and illness. The indirect costs could more than double the direct losses. Further, these costs can vary substantially depending on the location. Under RADTRAN III, the costs of an accident in an urban area could be over ten times greater.
- We recommend here that a real accident scenario for an urban area such as Las Vegas be constructed. The actual road and rail locations should be considered relative to business locations, population densities, and so on. The effect on Las Vegas and the state of Nevada of an extended time for

evacuation and interdiction should be incorporated into economic cost and health effect estimates.

- The RADTRAN III model must be further refined to incorporate indirect economic costs in both rural and urban areas.
- At a maximum of $500 million, coverage under the Price-Anderson Act is clearly inadequate. Congress must take another look at this matter. Our review of accident consequences leads us to conclude further that states will need assistance in preparing for emergencies.

Table 1. Dose Rates With and Without Neutron Shield*

NLI 1/2 Truck Cask

Decay Time	Fuel Cavity	Neutron Shield	Dose Type	Dose Rate in mr/hr Surface	1 Meter	2 Meter
5 yr	Dry	Wet	Neutron	1.743	0.4191	0.2148
			Gamma	3.565	0.9206	0.4724
			Total	5.308	1.3397	0.6872
5 yr	Dry	Dry	Neutron	77.19	18.92	9.148
			Gamma	3.28	0.96	0.53
			Total	80.47	19.88	9.678

IF 300 Rail Cask

Decay Time	Fuel Cavity	Neutron Shield	Dose Type	Surface	1 Meter	2 Meter
5 yr	Dry	Wet	Neutron	7.175	2.211	1.191
			Gamma	8.976	2.718	1.406
			Total	16.151	4.929	2.596
5 yr	Dry	Dry	Neutron	255.27	78.9	40.08
			Gamma	5.34	1.97	1.14
			Total	260.61	80.87	41.22

* Data from (Parks85). Under the column Neutron Shield, "dry" means the loss of neutron shielding.

Table 2. Fractional Occurrences for Truck Accidents

Accident Severity Category	NUREG-170(1) Pub Date 12/77	User Guide RADTRAN II(2) Pub Date 2/83	Envl Assment RADTRAN II(3) Pub Date 6/83
I	0.55	0.49	0.60
II	0.36	0.32	0.39
III	0.07	0.14	2.460E-03
IV	0.016	0.032	2.460E-06
V	0.0028	6.393E-03	2.751E-06
VI	0.0011	2.785E-03	3.044E-06
VII	8.5E-05	2.165E-04	NA
VIII	1.5E-05	3.997E-05	NA

(1) = (NRC77), (2) = (Madsen83), (3) = (DOE83)

Table 3. Fractional Occurrences for Train Accidents

Accident Severity Category	NUREG-170(1) Pub Date 12/77	User Guide RADTRAN II(2) Pub Date 2/83	Envl Assment RADTRAN II(3) Pub Date 6/83
I	0.5	0.41	0.62
II	0.3	0.25	0.37
III	0.18	0.30	2.460E-03
IV	0.018	3.04E-02	2.460E-06
V	0.0018	3.43E-03	2.751E-06
VI	1.3E-04	2.76E-04	3.044E-06
VII	6.0E-05	1.29E-04	NA
VIII	1.0E-05	2.26E-05	NA

(1) = (NRC77), (2) = (Madsen83), (3) = (DOE83)

Table 4. Failure Thresholds for Release from Spent Fuel to Cask Cavity due to Impact Rupture. Comparison Between Sandia Workshop and Modal Study

Cask Orientation	Sandia Wrkshp	Modal Study[3]
Side Impact	71 g to rupture[1] 28 mph cask velocity[2]	>41 g, 10% rupture >100 g, 100% rupture
End Impact	38 g to bend[1] 41.4 mph cask velocity[2]	

1 (Rhyne79)
2 (PNL78)
3 (Fischer87)

Table 5. Failure of a Truck Cask, Allowing Release from Cavity to the Environment. Comparison Between Sandia Workshop and Modal Study

Cask Orientation	Closure Seal Failure Sandia Wrkshp	Modal Study[3]
Side Impact	40 mph cask velocity[2]	S_1 strain, 45 mph S_2 strain[a], 60 mph S_3 strain[b] impossble
End Impact	48 mph cask velocity[2]	S_1 strain, <40 mph S_2 strain[a], 45 mph S_3 strain[b], 80 mph
Puncture	Not investigated	Not investigated

1 (Rhyne79)
2 (PNL78)
3 (Fischer87)

a S_2 strain: Radiation releases within regulatory limits. Impact to fail closure seals not estimated.

b S_3 strain: Radiation releases would exceed regulatory limits.

Table 6. Total Fraction of Material Aerosolized and Released from Spent Fuel to the Environment.

Radionuclide	Impact[a]	Impact & Burst[b]	Impact, Burst & Rupture[c]
Co-60	1.0E-1	1.0E-1	1.0E-2
Noble Gases	3.0E-5	1.0E-1	1.0E-1
Cs-134	8.0E-6	3.0E-4	1.0E-3
Cs-137	8.0E-6	3.0E-4	1.0E-3
I-129	8.0E-6	4.0E-4	4.0E-3
Sr-90	5.0E-7	4.0E-6	9.0E-7
Ru-106	---	1.0E-6	4.0E-5
Actinides	5.0E-7	3.0E-6	9.0E-7

[a] Scenario 2, (Wilmot81)
[b] Scenario 4, (Wilmot81)
[c] Scenario 5, (Wilmot81)

Table 7 Cost Values for Economic Analysis in RADTRAN III
(all values updated to 1982$, (Madsen86))

Category		Cost ($)	Comment
Survey Cost		$100,000/km^2	NRC80
Purchase Crops		$35,000/km^2	NRC75
Security		$140/km^2/day	NRC80
Evacuation		$18/person/day	NRC75
Personal income loss--rural	& suburban	$16/person/day	NRC75
	--urban	$160/person/day	10x greatr
Deep plowing		$110,000/km^2	NRC75
Scrape & bury (low)		$220,000/km^2	NRC75
Scrape & bury (high)		$500,000/km^2	2x low
Dwelling cleanup--rural (low)		$1800/person	NRC75
	--rural (high)	$2300/person	NRC75
Permanent relocation--	rural&suburban	$3874/person	NRC75
	--urban	$38740/person	10x greatr
Land value	--rural	$170,000/km^2	NRC75
	--suburban	$23,000/person	NRC75
	--urban	$230,000/person	10x greatr
Extensive tilled land cleanup		$1 million/km^2	Scrape & bury twice; waste disposal $500/acre reclaim land $1150/acre
Raze & rebuild--rural		$29 million/km^2	Ref 20,21*
	--suburban	$71 million/km^2	Ref 20,21*
	--urban	$3.6 billon/km^2	Ref 20,21*
Single family unit cleanup	--low	$366/person	NRC75
	--high	$1172/person	NRC75
Multi-family cleanup--low		$40/person	NRC75
	--high	$374/person	NRC75
High density bldg cleanup (>6 flrs)	--low	$20/person	NRC75
	--high	$187/person	NRC75
Public area cleanup	--low,suburban	$53/person	NRC75
	--low,urban	$530/person	10x greater
	--high,suburban	$560/person	NRC75
	--high,urban	$5600/person	10x greater
Park&Cemetery--low,suburban		$39/person	NRC75
	--low,urban	$390/person	10x greater
	--high,suburban	$51/person	NRC75
	--high,urban	$510/person	10x greater
Commercial areas	--low,suburban	$28/person	NRC75
	--low,urban	$280/person	10x greater
	--high,suburban	$1421/person	NRC75
	--high,urban	$14210/person	10x greater
Corporate income loss	--suburban	$7/person/day	NRC75
	--urban	$70/person/day	10x greater

Relocate government agencies	$670/person	NRC75

*Cost estimates by major contractors and municipalities that had suffered major disasters necessitating widespread removal.

Table 8. Contaminated Areas from a Severe Spent Fuel Accident, Category VI

Accident Class	Radiation Release (Ci)	Level of Contamination ($\mu Ci/m^2$)	Contaminated Area (km^2)
Impact, Burst and Oxidation	1380*	10	2.2
		5	4.3
		1	22
		0.5	45
		0.2	110

*Activity for noble gases is omitted. Data from (Sandquist85).

Table 9. Clean-up Costs for a Rural Area Under RADTRAN III

Contamination Level	Decontamination Procedure	Options* 1	2	3
0.1 < DF < 1	One survey	$99.00	$99.00	$99.00
990 km^2	Purchase crops	17.33	17.33	17.33
1 < DF < 20	Deep plow once & reseed	11.5		
104.6 km^2	Land value			17.78
	Purchase crops (½ land tilled)	1.84		1.84
	Two surveys	20.92		20.92
	Dwelling cleanup (low)	1.13		
	Evacuation (10 d;10 d & perm rel)	0.113		2.431
	Security (10 days;t)	0.146		346.36
	Personal income loss (10 d;1 yr)	0.10		3.665
	Subtotal	35.749	35.749	392.996
20 < DF < 40	Scrape & bury (½ land tilled)	0.7		
2.8 km^2	Land value			0.476
	Purchase crops	0.049		0.049
	Deep plow twice (½ land untilled)			
	Two surveys	0.56		0.56
	Dwelling cleanup (high)	0.039		
	Evacuation (10 d;10 d & perm rel)	0.003		0.068
	Security (10 days; t)	0.004		20.69
	Personal income loss (10 d;1 yr)	0.003		0.098
	Subtotal	1.358	1.358	21.941
DF ≥ 40	Interdict, land value	0.447		0.447
2.63 km^2	Extensive cleanup (½ land tilled)		1.315	
	Scrape & bury twice (½ untilled)		1.315	
	Survey (one;two)	0.263	0.526	0.526
	Buildings (raze & rebuild)		76.27	
	Evacuation (10 d & perm reloc; t_4; 10 d & perm reloc)	0.064	0.134	0.064
	Security (t;1/3*t_4;t)	21.45	0.058	21.45
	Personal income loss (1 y;t_4;1 y)	0.092	0.120	0.092
	Subtotal	22.316	79.738	22.579
		======	======	======
	TOTAL	$175.75	$233.18	$553.85

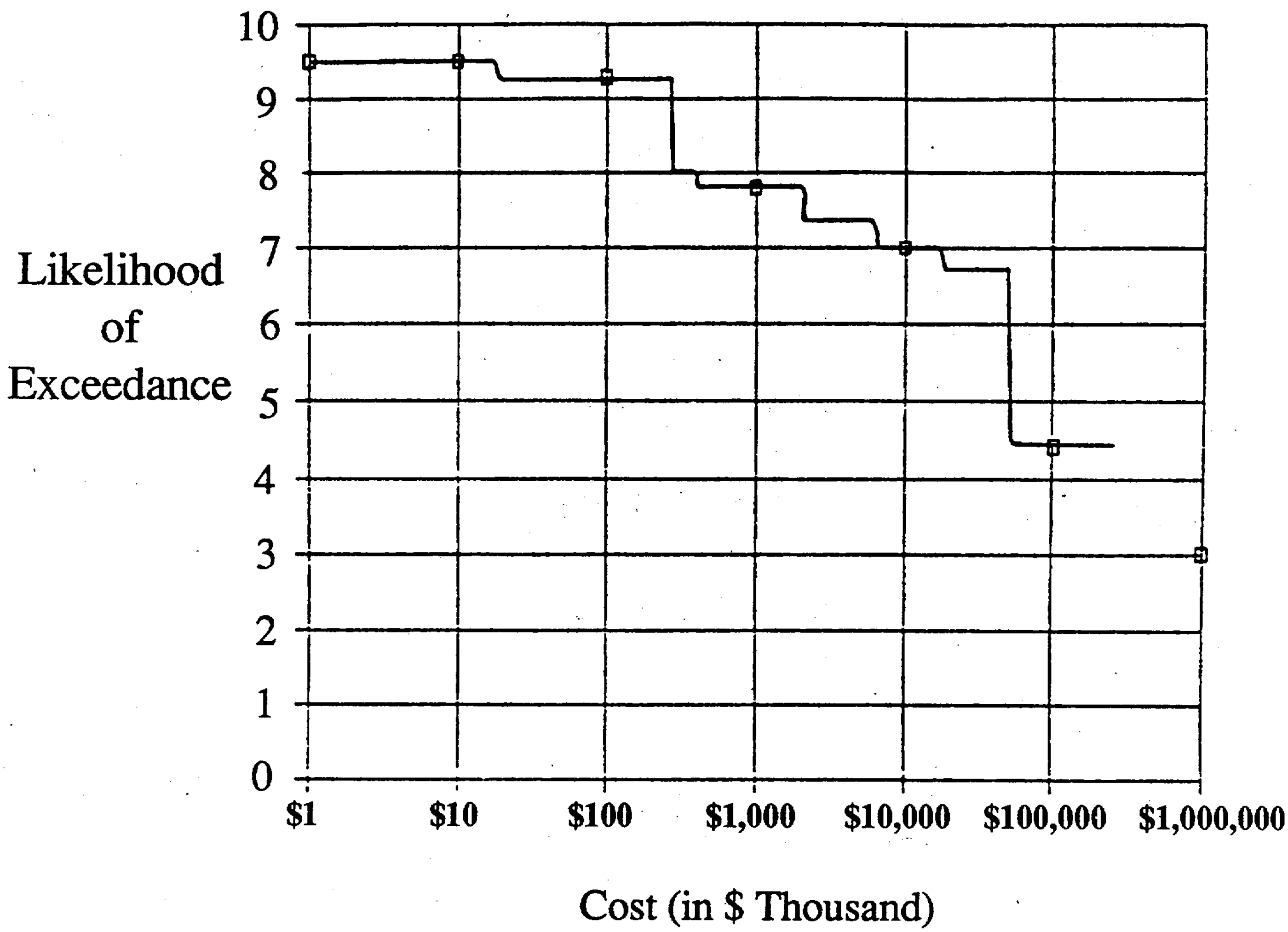
* All costs in millions of dollars.
t = time required for radioactive decay to reduce to contamination to criterion level, 0.2 μCi/m^2; Assuming Cs-137 contamination, 64.8 yrs to reduce contamination in region 1<DF<20, 144.6 yrs in region 20<DF<40, and 159.6 yrs in region DF≥40.
t_4 = time required to raze and rebuild, 180 * A_4 days, where A_4 = 2.63 km^2.

Table 10. DEFICIENCIES IN RADTRAN III.

Category	Subcategory	Comments
Incident-Free	Neutron dose not included;	For rail casks, neutrons cause up to 50% of dose;
	Gamma reflection dose not included;	Dose due to scatter of gamma rays from sky and ground;
	Line source	Cask radiation source is line, not point
Accident Severity	Category VII and VIII accidents excluded;	High consequence accidents eliminated due to low probability;
	Puncture not included;	Accident severity function of only impact and fire;
	Human error/sabotage;	Difficult to quantify, but enhances probability and consequences of major accident;
	Data reliability	Accident data under-reported; RADTRAN III does not distinguish between data and engineering judgment, nor place confidence limits
Health Effects	Dose/response factor not conservative;	Recent Japanese data implies more cancers/rem exposure;
	Accident scenario not realistic	Lung dose and fatalities could vary by orders of magnitude depend on realistic;
Economic Parameters	Accident and cleanup scenarios not realistic Social and political assumptions must be reconsidered;	Costs could range from $176 million to $ multi-billion and require from 10 days to over a century for decon;
	Indirect costs not included	Could more than double direct costs.

Fig. 1 Cost Curve

Nevada High-Level Waste Shipments



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