Transportation Scenarios For Risk Analysis

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ABSTRACT

Transportation risk, like any risk, is defined by the risk triplet: what can happen (the scenario), how likely it is (the probability), and the resulting consequences. This paper evaluates the development of transportation scenarios, the associated probabilities, and the consequences. The most likely radioactive materials transportation scenario is routine, incident-free transportation, which has a probability indistinguishable from unity. Accident scenarios in radioactive materials transportation are of three different types: accidents in which there is no impact on the radioactive cargo, accidents in which some gamma shielding may be lost but there is no release of radioactive material, and accident in which radioactive material may potentially be released. Accident frequencies, obtainable from recorded data validated by the U.S. Department of Transportation, are considered equivalent to accident probabilities in this study. Probabilities of different types of accidents are conditional probabilities, conditional on an accident occurring, and are developed from event trees. Development of all of these probabilities.

INTRODUCTION

Many people unfamiliar with radioactive materials transportation appear to think that such transportation is riskier and more hazardous than transportation of other goods and materials, and that the risk is from exposure to ionizing radiation. These beliefs persist in spite of the many analyses of radioactive materials transportation that show that the radiological risks are negligible compared to ordinary accident risk. These results are difficult to convey because there is no record at all of radiological damage from radioactive materials transportation, so that the analyses of such transportation cannot be benchmarked against data and measurements; benchmarking can only be done using surrogates (see, for example, Steinman, et al., 2002).

Dispelling belief in the exaggerated risk of radioactive materials transportation is probably impossible, and is not the intent of this paper. This paper presents the results of a transportation analysis in a context framed by the definition of risk and the risk triplet, so that those who try to explain risks of transporting radioactive materials understand the foundation for these risk analyses.

THE RISK TRIPLET

Risk is usually defined by the risk “triplet”:

- What can happen (the scenario)?
- How likely is it (the probability)?
- What if it happens (the consequence)?

A quantitative risk is calculated by multiplying the probability and consequence for a particular scenario. The probability of a scenario is always less than or equal to one, because the maximum probability of an event is one (100%); an event with 100% probability of occurrence is an event that is certain to happen. In reality, very few events are certain to happen or certain not to happen (zero probability). The probability of most events is between these two extremes. Transportation accidents involving large trucks, for example, have a very low probability. The probability of a traffic accident in the United States is about 1/100,000 per mile according to the Department of Transportation Bureau of Transportation Statistics (DOT, 2007), and the probability of a particular traffic accident scenario that includes vehicles carrying casks of radioactive material is much smaller still.

ROUTINE, INCIDENT-FREE TRANSPORTATION

The Nuclear Regulatory Commission (NRC) regulates the external dose rate from a transported package of radioactive material to 0.1 mSv/hour at two meters from the cask or from the side of the vehicle carrying the cask. The external dose rate is usually less than this and is often so small as to be unmeasurable. For many years, in order to be conservative, analyses of the impacts of routine transportation assumed that all transported radioactive packages emitted ionizing radiation at the maximum rate. More recent studies (Weiner and Dunagan, 2008) use the actual measured external dose rate. The impact of various parameter values on the risks from routine transportation are presented here for a sample problem: transportation of transuranic (TRU) waste to the Waste Isolation Pilot Plant (WIPP) in southeastern New Mexico. Highway routes to the facility are shown in the map in Figure 1(the facility has no rail access).

Figure 1 Highways Used for Transportation to the Waste Isolation Pilot Plant

Risks to various receptors are calculated using RADTRAN Version 6 (Weiner, et al, 2009). RADTRAN models the transportation vehicle as a sphere moving along the route (Figure 1) with the transport index (TI) as a virtual radiation source at the center of the sphere.

When the distance to the receptor (*r* in Figure 1) is much larger than the critical dimension, RADTRAN models the dose to the receptor as proportional to $1/r^2$. When the distance to the receptor *r* is similar to or less than the critical dimension, as for crew or first responders, RADTRAN models the dose to the receptor as proportional to $1/r$. The dose calculated by the RADTRAN spherical model overestimates the measured dose by a few percent (Steinman et al., 2002).

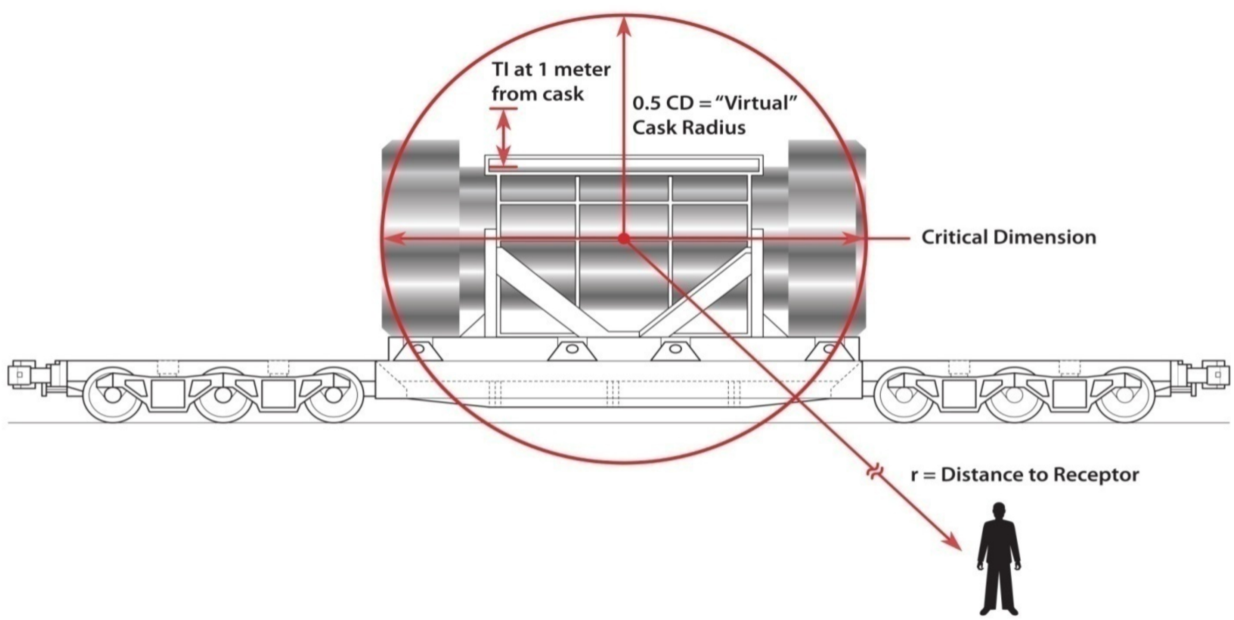

Figure 2. RADTRAN model of the vehicle in routine, incident-free transportation. The cask in this diagram is positioned horizontally, and the critical dimension is the cask length. The TI is the transport index, and is the dose rate in 0.01mSv/hr (mrem/hr) at one meter from the cask surface.

Figure 3 shows the effect of the TI on risk from a single shipment of transuranic waste that travels from Brookhaven National Laboratory on Long Island to the WIPP along interstate highways 81, 50, and 20 (Figure 1). This effect could be anticipated since the TI, the external dose rate, is a linear coefficient of the dose rate integral, shown in Equation (1)

$$D = \frac{PD * L * TI}{V} \int_{\infty}^{\infty} \int_{xmin}^{xmax} \frac{[(e)]^{-\mu r}) * B(r)}{r\sqrt{(r^2) - x^2}} dxdr \qquad (1)$$

Where D = the collective dose
PD = population density
L = route segment length
V = vehicle speed
TI = vehicle dose rate at one meter
μ = absorption coefficient of air
r = distance of the receptor from the moving vehicle
x = perpendicular distance from the transportation right of way
B(r) = buildup factor

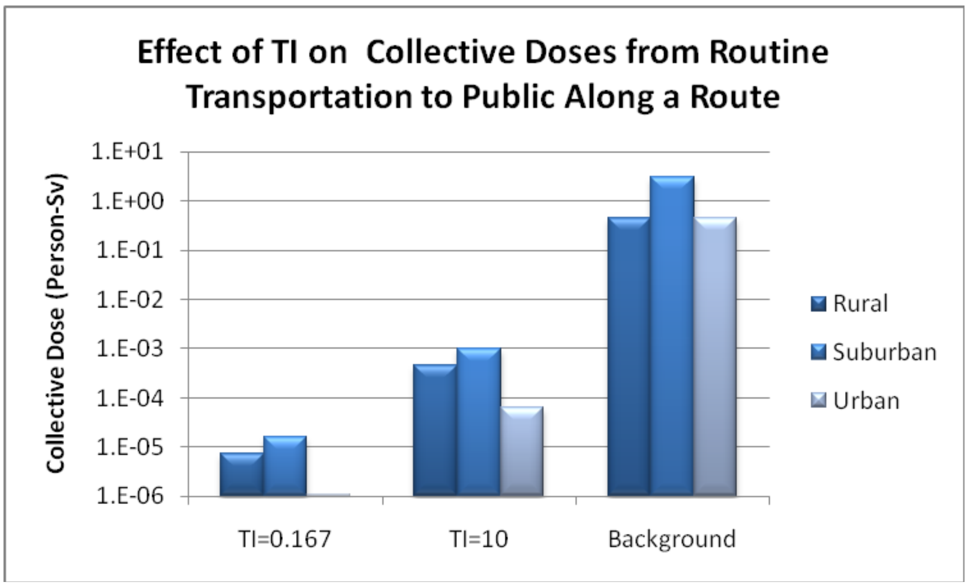

Figure 3. Effect of TI on collective doses from routine transportation – logarithmic vertical scale.

Figure 3 also compares background dose (assuming a U.S. average background of 0.0036 Sv per year, or 4.1 x 10^{-7} Sv/hour) to the dose from a shipment to the public along the route. The comparison is even more dramatic when the vertical scale of the graph is linear rather than logarithmic, as in Figure 4.

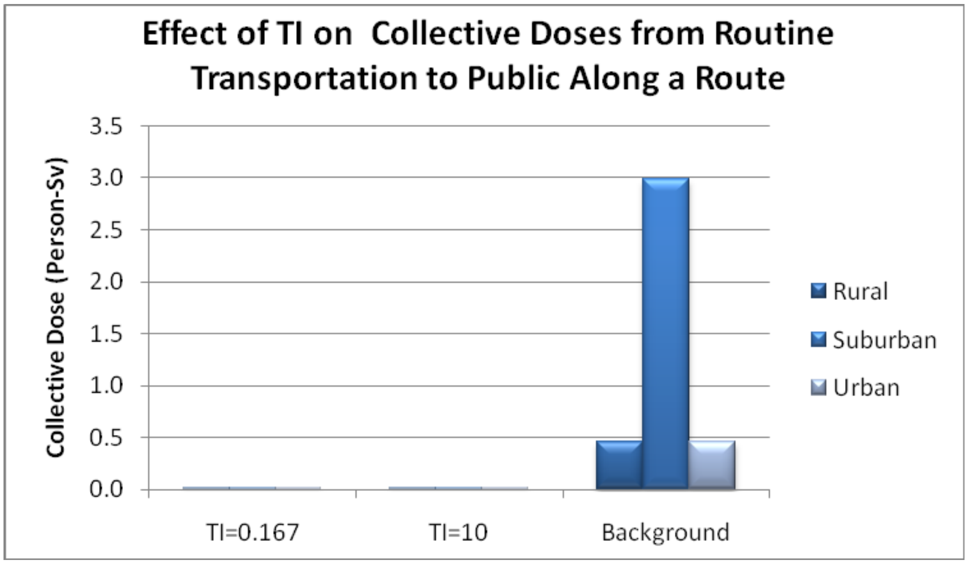

Figure 4. Effect of TI on collective doses from routine transportation – linear vertical scale.

Table 1 shows the data for Figures 3 and 4.

Table 1. Collective dose (person-Sv) from a routine shipment

Route segment type	TI=0.167	TI=10	Background
Rural	7.4E-06	4.5E-04	4.6E-01
Suburban	1.6E-05	9.8E-04	3.0E+00
Urban	1.1E-06	6.3E-05	4.6E-01
Total	2.5E-05	1.5E-03	3.9E+00

The collective dose or risk (which is in this case equivalent to dose) to the public along a transportation route from a cask routinely transporting radioactive material is the sum of the background collective dose and the collective dose from the shipment. For example, the total collective risk along this route, assuming a realistic TI of 0.167, is 3.900025 person-Sv for each shipment, and 3.900000 person-Sv without a shipment. If the maximum TI of 10 is assumed, the total collective risk along this route is 3.9015 person-Sv for each shipment, and 3.9000 person-Sv without a shipment.

The number of shipments estimated to go from Brookhaven to the WIPP is 658. Assuming TI= 0.167, the dose to the public from the shipments alone, neglecting background, is 0.0165 person-Sv ($2.5 \times 10^{-5} \times 658$). If the unrealistic assumption is made that the 658 shipments follow each other closely in a continuous stream and thus assume the same background dose to the public along the route, the total collective dose is 3.9165 person-Sv. If a more realistic assumption is made: that there are 10 shipments a day for a total of 65.8 days,

- the total collective background dose during the shipments = 65.8*3.9 = 256.6 person-Sv

- the total collective dose from the 658 shipments is 0.0165 person-Sv
- the total collective dose from background plus shipments is 256.6165 person-Sv.

This example illustrates several points about risks of transporting radioactive materials:

- The doses from routine shipments of radioactive materials are negligible when compared to background radiation exposure.
- For residents along the route, the difference between a shipment and no shipment is <u>not</u> the difference between the dose from a shipment and nothing, but the difference between the dose from the shipment plus background and the dose from background alone.
- "Collective dose" is itself an arbitrary concept, because an increase in collective dose is not an increase in radiation exposure, but an increase in the number of people exposed. It has been said that "if the individual is not harmed, the group is not harmed" (ACNW, 2008, p. 201).
- The practice of multiplying the dose to the public from a single shipment by the number of shipments is questionable. The human body does not accumulate radiation dose, but accumulates the tissue damage, if any, that the dose delivers. The damage is mitigated by recovery between doses (as is illustrated by the fractionation of large therapeutic doses of ionizing radiation). In effect, the dose delivered by 658 shipments made at the rate of one or two shipments per day has approximately the same effect as the dose from a single shipment.

TRANSPORTATION ACCIDENTS

There are potentially two types of accidents involving vehicles carrying radioactive materials: accidents in which the radioactive cargo is affected and accidents in which that cargo is not affected.

<u>Accidents in which the radioactive cargo is not affected</u>

The most likely accident scenario involving a vehicle carrying a Type B cask is one in which the cask is not affected, or that any effect of the accident on the cask does not result in any dose rate increase to the public. If a Type B cask is in an accident, the conditional probability that the accident is of this type is more than 99.99 percent (Spring, et al, 2000, Chapter 7). This type of accident is the only one that has ever actually been observed. The proximate effect of this type of accident is that the vehicle and cask sit at the accident location until the cask can be transferred to another vehicle or until the cask and vehicle can be moved. The dose to the maximally exposed individual (MEI) from a Type B cask accident after which the cask is stationary for ten hours is about one microsievert. As with doses from routine shipments, the source is the external dose rate from the cask, modeled as a virtual source at the center of the cask. The background external dose is about four microsieverts. The MEI dose and the collective dose from this type of accident would therefore be about ¼ background. The "dose risk" depends on the accident frequency along the particular route. For the route from Brookhaven to the WIPP, the collective dose risk from the accident would be 0.017 person-Sv; while the total background dose (and risk) would be 1.2 person-Sv.

Accidents in which the radioactive cargo is affected.

Although a number of Type B casks carrying fuel cycle material have been in traffic accidents, these accidents have not involved release of radioactive material. The only traffic accident scenario that could result in release of radioactive material is failure of the cask seals, either by ire or impact. The only other accident scenario that could result in an increased dose to the public is the thinning or loss of lead gamma shielding, which would of course occur only in a cask that uses a lead gamma shield. Thus assessment of accident risk depends on the postulation of an extra-regulatory accident that stresses the cask more severely than the test sequence of 10 CFR 71.73.

The very small conditional probabilities of such accidents can be estimated only by examining the frequency of similar accidents that have involved vehicles like those that carry very radioactive materials: very large semi-detached trailer trucks and railcars carrying large casks. The partial event tree of Figure 5 (Mills, et al, 2006) illustrates how conditional probabilities can be developed. For illustrative purposes, consider a highway collision between a large semi carrying radioactive cargo and a large semi carrying gasoline. From Figure 5, assuming that the truck carrying the radioactive cargo is in an accident, the probability that this truck hits an object that is not stationary is 0.82, the probability that the non-stationary object is a gasoline tanker truck is 0.00246, so that the net conditional probability of this accident is

$$0.82*0.00246 = 2.01 \times 10^{-4}$$

The average accident frequency for large semi trucks in the U.S. since 1996 is 2×10^{-6} per km (DOT, 2008), so that for a 3000 km trip across the U.S, the accident probability would be 0.006 and the probability that the truck carrying radioactive material collides with a gasoline tanker truck during this trip is

$$0.006*2.01 \times 10^{-4} = 1.2 \times 10^{-6}$$

This is the probability that such a collision occurs[1] but does not include the probability that fuel leaks from the tanker or that the leaked fuel is ignited and the burning fuel pools and engulfs the cask for more than 30 minutes.

[1] The use of a frequency as a probability depends on the application of Bayes' Theorem.

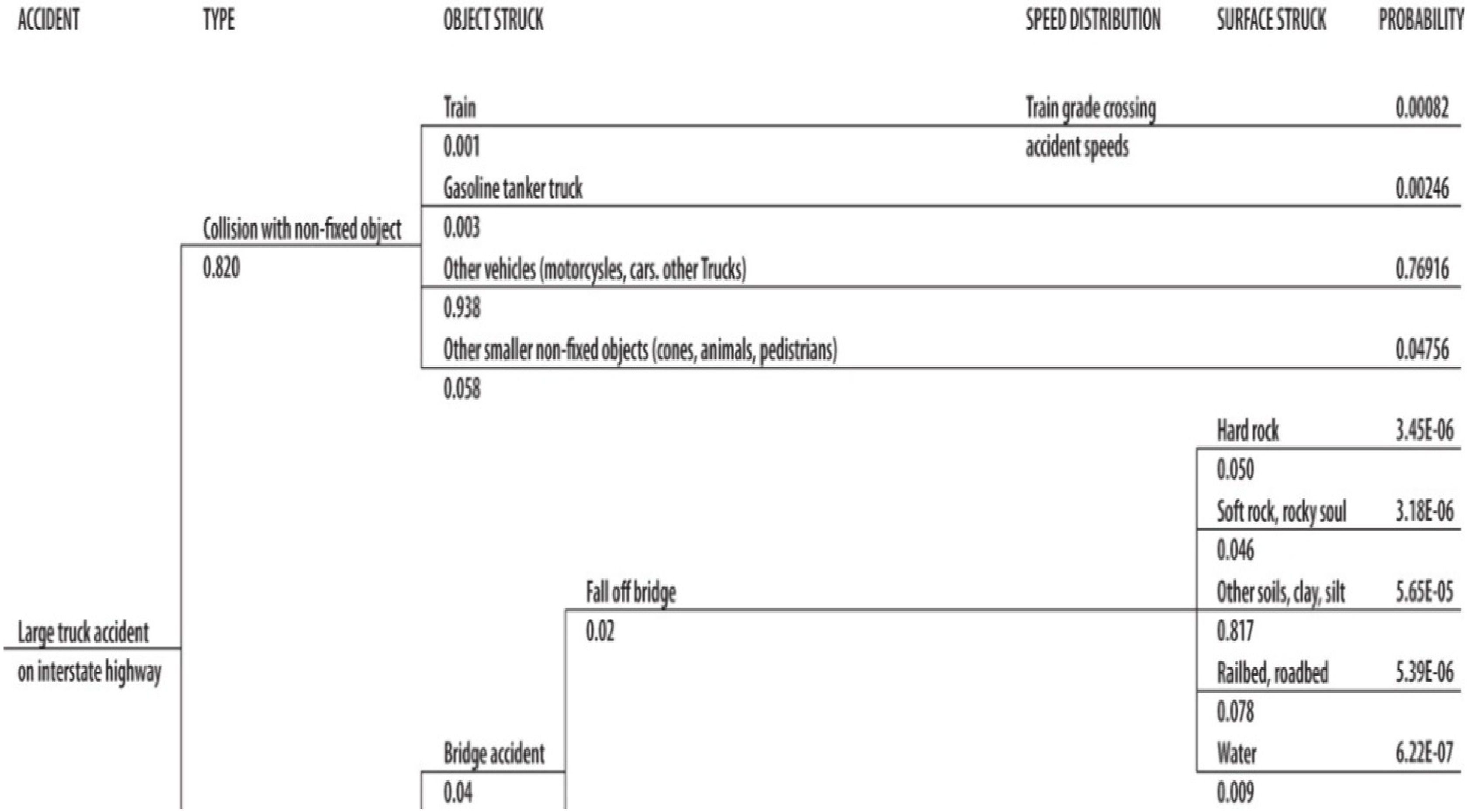

Figure 5. Part of a truck event tree (from Mills, et al, 2006).

In order to damage a Type B cask sufficiently to either melt a significant quantity of lead or fail the cask seals, the resulting fire must engulf the cask and burn for a sufficiently long time. These probabilities (except for the second) are probably less than one, possibly much less, but in the interest of conservatism and lack of data, let us assume the following probabilities:

Probability of a fuel leak resulting from the collision: 0.9
Probability that the leaked fuel is ignited: 1.0
Probability that the burning fuel pools and engulfs the cask: 0.6
Probability that the engulfing fire burns for more than 30 minutes: 0.6
Net conditional probability = 2.01×10^{-4}*0.9*1.0*0..6*0.6 = 6.5×10^{-5}

And the net probability is

$$0.006*6.5 \times 10^{-5} = 3.9 \times 10^{-7}$$

Thus, the <u>maximum</u> probability of a collision like that described resulting in either a release of radioactive material, or a loss of lead shielding, or both, is 1.2×10^{-6} and a very slightly less conservative probability is 3.9×10^{-7}. For a shorter trip the probability would be less.

The probabilities that the spilled gasoline pools to form an engulfing fire, and that the tanker contains enough fuel for the fire to burn long enough to fail the seals or the lead shielding have been estimated as much less than 1.0. The net probability of a fire that exceeds the regulatory fire in intensity and duration is exceedingly small, of an order of magnitude 10^{-10} or less (Volpe, 2006; Mills,et al 2006). Similar considerations have been applied to impact-only accidents, and show that such probabilities are also exceedingly small..

The National Research Council (National Research Council, 2006, p. 4) suggests that

> *"…radiological health and safety risks associated with transportation of spent fuel are generally low, with the possible exception of risks from releases in…very long duration, fully engulfing fire."*

The approximate risk for the accident scenario discussed suggests that the risk of release in very long duration fires is low also.

The consequence of a fire scenario accidental release provides an interesting insight. Figure 6 shows the dose to the maximally exposed individual (the MEI dose) as a function of distance from the source for the case where the accident involves high-level radioactive waste cask (RH-72b) and a car fire (release elevation: 100 m; emitted heat: 1000 calories). Data from an impact-is shown on the graph for comparison. Conditions in the two cases were the same except for the fire, and the same model was used for both. As the graph shows, an elevated release results in moving the maximum dose to the MEI downwind; the maximum occurs at

$$x = H/\sqrt{2}$$

where x is the downwind distance in meters and H is the release height in meters (Wark et al. 1998). The dose to the MEI from the fire accident, as modeled, is also much less than the dose from the no-fire accident at distances less than a kilometer from the accident. In the particular scenario studied (Weiner and Dunagan, 2008), the doses from the two accidents are the same, and are about 100 mrem, at about 7 km from the source.

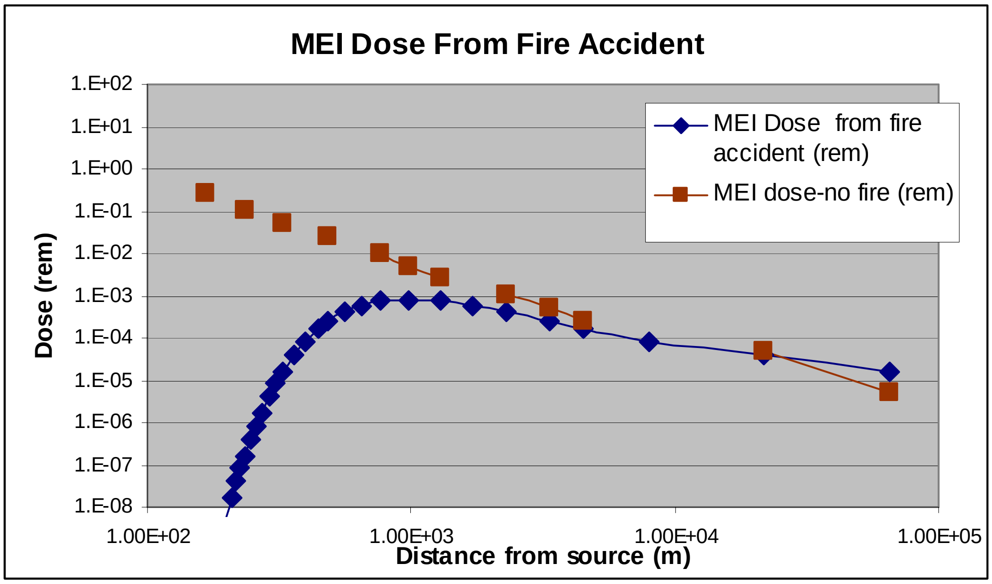

Figure 5 MEI doses from an accident that involved a fire and one that did not involve a fire.

The MEI dose is a more meaningful indicator of radiation exposure than collective dose, because the collective dose is a function of the number of people exposed to the plume rather than the amount of radioactive material released. Even for the no-fire accident in this scenario, the MEI dose was of the same order of magnitude as the average annual background dose.

OBSERVATIONS

There is no transportation scenario, routine or accidental, that would result in a radiation dose to the public that is significantly larger than background. Radiation doses to the public from routine transportation are indistinguishable from background. This result is valid even using conservative models and conservative parameter values. This result is probably not valid if there is a deliberate attack on a radioactive materials shipment, but the deliberate attack scenario is not part of this analysis.

The magnitude of a collective dose depends on the number of individuals exposed rather than on the intensity of radiation from the source. Comparison of collective doses, e.g., for the same shipment on different routes, is a comparison of populations, not of radiation exposure. Thus collective dose should be used cautiously, and as a mthod of comparing routes, not as an absolute indocator of health effects.

Accidental release of radioactive material from a transportation package in a fire can result in an elevated plume of aerosolized radioactive material. The radiation dose to the public from such an elevated plume is actually smaller than from a ground level release that would occur in the absence of a fire, though the number of people under the plume may be larger. Commnication of this result should emphasize that the dose to the maximally exposed individual is a better indicator of radiological effect than collective dose to the public.

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